TOOLBOX FOR NAVIGATING THE LAND-USE IMPACTS OF THE AUTONOMOUS VEHICLE ECOSYSTEM

FINAL TOOLBOX APPENDICES

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Appendix A: The historical and present-day links between transportation and land use

Transportation technologies play a major role in influencing the shape of the urban environment. In turn, the shape of the urban environment can have a major role in influencing the use of transportation technologies. Human activity has been defined by the link between the homes and communities in which people dwell, work, and recreate—and the means of travel they use to move within and between them (Clark 1958). As transportation technologies have changed over time, so has the ability to move both people and freight, and these changes have had influence on the ways that people live. At the same time, the types of environments in which people live have had great influence on the means of transportation they use to get around. Together, technologies and land use patterns go on to co-produce "distinct ways of dwelling traveling and socializing in, and through" time and space (Scheller and Urry 2000: 738). The development of automated or AVs, like that of many previous transportation technologies, could have considerable influence on human living and working patterns. And policymakers could shape this process of change through the development of regulations and plans designed to influence AV rollout.

The purpose of our research is not to detail AV technology specifically. Others have made projections related to how AVs might influence passenger transportation systems (Fagnant and Kockelman 2014) or planning for the impacts of automated freight at the state and local level (The Tioga Group, Inc. et al. 2023). Nor do we estimate how rapidly the technology will be implemented in countries around the world, which has been the task of other researchers. In a recent report, Kuciemba et al. (2023) develop a framework for estimating the future rollout of these vehicles and describe the different market and policy elements that could influence how quickly they saturate the market. But we are not yet at the point of being able to clearly determine when these vehicles will become commonplace; doing so would be a fool's errand given the continued uncertainty about when such technologies may be available and the exact specifications.

Even so, while technology related to vehicle automation has arguably been under development for more than a century, over the past decade, the technology has advanced considerably (Schwartz 2018). Based on the experience with past transformative transportation technologies, there is likely to be a major impact of AVs on land use—and land uses are likely to impact how AVs are implemented. While hardly a common sight, AVs are now being widely tested and, in some cases, used for paid transportation services. This makes understanding, and planning for, their relationships with the human-built environment even more important.

Our examination of extant scholarship makes certain points clear. First, technological determinism, or the idea that change in technology is the primary influence on human social relations and organizational structure, is an insufficient explanation for why people use certain transportation technologies and for the design of the environments in which we live. While it is true that new technologies can radically transform people's lives (think of the smart phone!), there is also plenty of evidence that the mere existence of a new technology does not predetermine certain outcomes. If that were the case, why are some new urban developments in the United States entirely oriented around car use, whereas others feature high levels of pedestrian and cycling activity?

Second, transportation technologies play a major role in influencing the shape of the urban environment, but the shape of the urban environment, too, can have a major role in influencing the use of transportation technologies. The introduction of affordable private automobiles and cheap trucking encouraged the development of an urban environment designed around roadways, incorporating single-family homes with integrated garages; big box stores, office parks, and strip malls with parking lots surrounding them; and a landscape of gas stations, motels, and auto repair facilities lining the highways from coast to coast. It also encouraged the proliferation of suburban sprawl. At the same time, the urban environment itself (combined with other transportation options) can mediate the role of a new technology. A majority of households in New York City, for example, have no car available,[1] likely to a large degree because of that city's density of population and employment that make traveling by car there often inconvenient.

Third, policy is influential in shaping the link between transportation and land use. Policymakers determine whether to allow for the widespread adoption of new technologies (e.g., in the face of safety risks), choose whether to subsidize their use (e.g., by using tax dollars to fund infrastructure), and implement associated regulations (e.g., by mandating parking requirements for new building construction). These choices can be contested and are often subject to disagreement and revisions throughout the lifecycle of a given technology. As such, policymakers have considerable opportunity to influence both transportation technologies and associated land uses, as well as their interactions.

We make these arguments largely in the context of transportation technologies that are not AVs, meaning based on past experience with other technologies. We believe that though the specifics of AV technology are different, the manner by which they may influence the world around them—and be influenced by the world around them—can be projected at least to some degree by historical conditions.

We begin by defining our terms—what we mean by transportation technologies and land use—in boxes 1.1, 1.2, and 1.3. In the first section that follows, we offer insight into the ways by which transportation technologies and land use interact with, and influence, one another. We then turn to what recent research tells us in terms of the ways these interactions may occur in the context of AVs, before concluding by describing the general approach we are taking in this research program.

Box A.1 Defining Transportation Technology

Before we discuss links between transportation and land use, it is necessary to begin with a standard set of definitions. These definitions are inherently limited but help ensure that our discussion is concise and contextualized. We define new transportation technologies, then, as one or more of the following:

- *A new mode of transportation or transportation-related infrastructure* used for journeys. One example is the automobile. New modes may require specialized new infrastructure (e.g., railways in the case of trains), or they may be able to use existing infrastructure, though that infrastructure may need to evolve over time to accommodate changes (e.g., paved roadways were initially developed on behalf of cyclists, but were then adapted for car use).
- *New information* that is used to inform a mode of transportation's journey. An example of such new information is the geospatial data provided through satellites to software using the Global Positioning System (GPS), which pinpoints a vehicle's location on the world surface.
- *New services* provided using a mode (or multiple modes) of transportation. One example is the transport of freight on using containers. This type of service alters available transportation options, often through a combination of transportation modes and transportation information.

In theory, a new transportation technology could:

- Increase (or decrease) travel speeds between destinations, e.g., by moving more quickly or taking a more direct route.
- Reduce (or increase) the financial cost of transportation, e.g., by reducing the capital and labor cost per ton of freight.

- Reduce (or increase) the burden of travel, e.g., by making a trip safer, more comfortable, and/or more reliable.

- Some combination of the above, such as increasing cost while decreasing time, or increasing cost while reducing burden.

None of these changes is a given associated with a new transportation technology; for example, it is not clear whether AVs will be less expensive, more reliable, or safer than current modes of transportation, as we discuss below. Nevertheless, if these changes do occur, they have the potential to expand the use of transportation; if mobility becomes faster, cheaper, and less burdensome, it is natural to assume that people and goods would become more mobile. And, indeed, peoples' mobility in terms of the number of miles traveled has expanded tremendously over the past century (Fischer-Kowalski 2004; Leard, Linn, and Munnings 2019). But a transportation technology that fails to increase speeds, reduce costs, and/or reduce burdens could have no effect on those outcomes; even more likely is a technology that changes some parameters of transportation access in one direction while altering other parameters in another direction. Moreover, as we shall see, peoples' demand for mobility—by which we mean physical movement across space—is dependent on land uses.

Improvements in transportation technology are not necessarily applied evenly across geographies or individuals. A transportation technology that increases speeds but at a high cost may be transformative in terms of increased mobility for those who can afford it but provide less benefit for those who cannot (or even potentially harm them by reducing their access to the opportunities that get absorbed by those with increased mobility). Or a technology whose impact is spatially limited to only some geographies may influence travel patterns for people living in some areas, but not in others (Knowles 2006). People close to high-speed rail lines, for example, may benefit from dramatically improved mobility even if those further away do not.

Box A.2 Defining AVs

We define AVs as a form of new transportation technology (or, alternatively put, as a spectrum of technologies that can be combined for a single output). AVs, described quickly, combine an automated driving system with a vehicle to perform a dynamic driving task over a specific operational design domain within the public road right-of-way. An AV's strategic functions are defined by a human. The AVs we describe in this review—as well as the entire project that this accompanies—are capable of level 4 or 5 automation; they thus go beyond driver assistance technologies such as cruise control. *Autonomous* vehicles are different than *automated* vehicles, such as automated metros and people movers now common around the world; the key differentiating aspect is that autonomous vehicles operate on public roads, often shared with other vehicles and pedestrians, whereas automated metros and the like operate on fully separated rights of way. The key terms used in describing AVs are defined below (list from Freemark et al. 2022: 5–6):

- **Operational design domain (ODD):** The times, places, and conditions (such as weather) in which an AV, rather than a human driver, is designed to operate. An AV could have an ODD that applies to all roadways and all times, or the ODD could be limited to, for example, only limited-access highways, leaving driving on other types of streets to a human driver.

- **Automated driving system (ADS):** The term often used by regulators to describe the technology used to pilot an AV in cases where human drivers do not have to be engaged.

- **Dynamic driving task (DDT):** The operational and tactical functions required to operate a car in traffic, typically including lateral vehicle motion control (steering), longitudinal vehicle motion control (acceleration and braking), and monitoring the environment, including through event response, maneuvering, lighting, and signaling.

- **Levels of automated driving:** Represent the spectrum of AV operations, as defined by SAE International[2] and typically used by regulators. These levels include:
    - **Level 0:** No driving automation. Human controls every aspect of driving.
    - **Level 1:** Driver assistance. An automated system controls either the lateral or longitudinal elements of the DDT (such as through adaptive cruise control), with the driver performing the remainder of functions and supervising any automation.
    - **Level 2:** Partial driving automation. An automated system controls both the lateral and longitudinal elements of the DDT, with the driver performing the remaining functions and supervising any automation.
    - **Level 3:** Conditional driving automation. An automated system performs the full DDT under the relevant ODD (see below), but the user must determine whether and how to achieve a minimal risk condition (meaning moving the vehicle to a stop to reduce risks), if needed, and the user can become the driver if needed.
    - **Level 4:** High driving automation. An automated system performs all DDTs under the relevant ODD and transitions automatically to minimal risk condition if needed.
    - **Level 5:** Full driving automation.
- **Strategic functions:** Trip scheduling and selection of destinations and waypoints. These functions are outside the control of the AV system but are input either by the human rider or by the trip provider, such as the ride-hailing operator.

AVs may be implemented in both passenger and freight contexts. Because freight AVs do not have to carry humans at all, they may take a wide variety of form factors, from current-sized trucks to small-scale delivery vehicles, drones, and ships (The Tioga Group, Inc. et al. 2023).

Why do we consider AVs a form of new transportation technology? They redefine existing transportation modes (e.g., automobiles, buses, and trucks) or allow for new transportation modes (e.g., robotic goods transport devices) by collecting new information about the roadway. Using cameras and LiDAR, they can autonomously circulate between two points and navigate transportation environments that are not closed, meaning other modes, like human-driven cars and pedestrians, can enter their right of way. AVs could be used in the context of new services (e.g., all-night warehouse-to-home goods delivery), but those new services have yet to be introduced because AVs remain in development.

Box A.3 Defining Land Use

Let us now, finally, consider land use. We define it to include the following elements:

- The form of buildings in an area (e.g., towers versus single-family homes for residences). Building form could specifically include the shape of buildings to adapt to, or orient, different modes of transportation.
- The use of buildings or land in an area (e.g., for residences or for warehousing, or for both).
- The preservation of land for largely non-built needs (e.g., for natural or agricultural use).

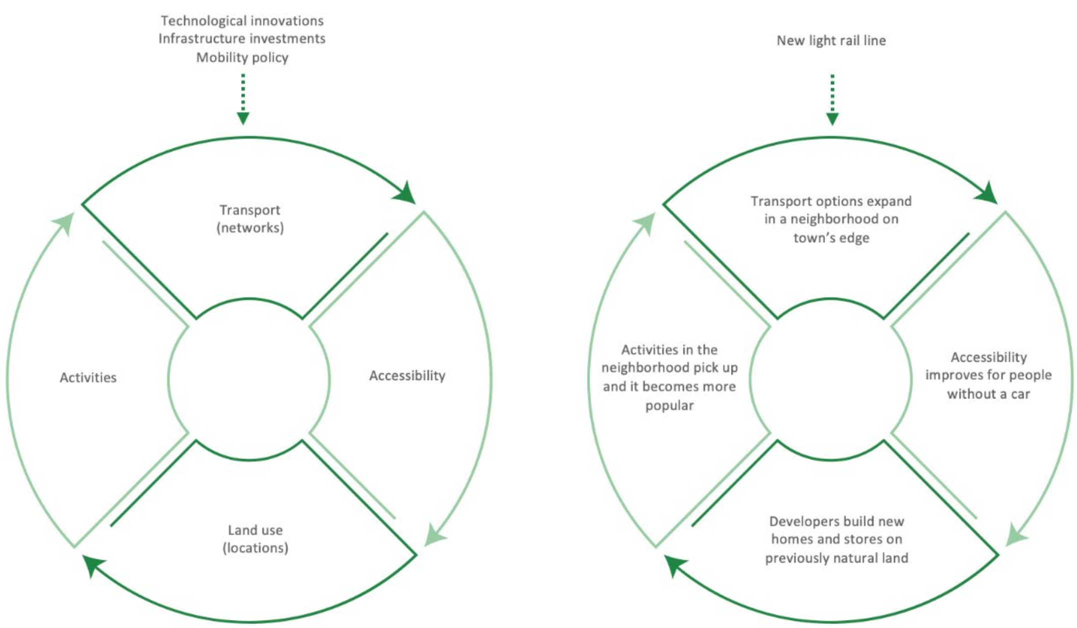
- Transportation infrastructure itself, meaning the facilities needed to convey and store vehicles in the transportation system.

Land use is different than land-use regulation. The latter is the system of laws that governments—typically local governments—use to determine what sorts of construction can be allowed where. Land-use regulations are typically important in determining eventual land uses, but the built environment of a city may not match what planners of that same city have identified as its planned future.

How do transportation technologies and land use influence one another?

Transportation and land use interact in a cycle (Figure A.1). Accessibility to a location has an impact on land use over time; the types of buildings in a place are influenced by whether there are transportation options to get there, if there are buildings, then, activities follow in those buildings. The positioning of activities in a location goes on to influence transportation networks, since transport evolves to meet the needs of the urban environment (Bertolini 2012).

Figure A.1 The Transportation–Land Use Feedback Cycle Illustrates the Multi-Directional Links Between Mobility and the Built Environment



Source: The authors, adapted from Bertolini (2012).

This cycle can be summarized as follows:

- Availability of *transportation* has a direct influence on accessibility, meaning that accessibility to a location (or, in general, to an adequate number and type of locations to fulfill life needs and wants) is only possible if there is a means of transportation to get there.

- *Accessibility*, in turn, influences the availability of activities, meaning that having access to a location influences whether anything to do will be there.

- Accessibility to a location has an impact on *land use* over time; the types of buildings in a place are influenced by whether there are transportation options to get there, if there are buildings, then, activities follow in those buildings—which then influences overall accessibility.

Finally, the positioning of *activities* in a location goes on to influence transportation networks slowly, since transport evolves to meet the needs of the urban environment.

Consider an example, also illustrated in Figure A.1: a city opens a new light rail line to a neighborhood on the edge of town. That area becomes accessible to residents without a car. Because of this accessibility, residents start using the area for Sunday picnics in the grass. Slowly, developers hoping to profit from this accessibility build new homes and stores on the previously natural land, bringing in a new set of activities. As the neighborhood becomes more popular, the light rail becomes increasingly popular, increasing crowding on trains, and ultimately increasing the burden of using the line; this diminishes accessibility. The city then invests in other transportation in the area, and the cycle continues.

How does transportation technology influence land use—and vice-versa?

How do transportation technologies influence land use? As we noted, new technologies could increase speeds, reduce financial costs, reduce travel burdens, or some combination of the three. Those changes could go on to produce some combination of the following impacts on land use:

- *Increased access to certain destinations*, increasing their property value and/or their comparative advantage in attracting jobs, retail, and other investments. Improved access to certain areas may encourage more people to move to certain areas over others (Baum-Snow 2007).

- *Allowing longer trips*, increasing the appeal of destinations at the edge of regions or increasing the ease of intercity trips (e.g., the light rail and high-speed rail examples, respectively). This could encourage development in previously inaccessible locales (see Ewing, Pendall, and Chen 2003), or generate increased long-distance trade, which could stimulate port development. The creation of the highway system, for example, decentralized both residences and jobs and reduced population densities within central cities; this may go on to alter which regions become more economically vibrant over time (Baum-Snow 2020; Baum-Snow et al. 2020).

- *Altered modal choice*, shifting people from one less-appealing mode of transportation to another. This could reduce the attractiveness of, and future growth in, urban areas built around an older transportation technology (as we have seen in areas around canals).

- *Modified building designs* to meet the needs of new technology. This could generate homes with driveways for automobiles, for example, or shopping in strip malls with copious parking rather than downtowns. The large distribution warehouses that exist on the edge of many cities, with ports allowing tractor-trailer trucks to back in, are buildings designed for transportation modes.

- *Variation in neighborhood design* to accommodate infrastructure. For example, city blocks may be bulldozed to make way for a highway or redeveloped at high densities as part of a joint development with a rail station.

- *Increased demand for land* to accommodate technology materials, production, operation, maintenance, and disposal facilities related to that technology.

In some cases, the impacts of a transportation technology on land use are most felt in terms of the infrastructure. The construction of highways involved demolition of central-city neighborhoods, altering the land use therein. But in other cases, it may be dependent on the *use* of that infrastructure. Knowles, Ferbrache, and Nikitas (2020), for example, argue that transit-oriented development is most successful when combined with frequent transit service, not just any sort of service.

As we have noted, though, the links between transportation and land use are not unidirectional. Land-use can encourage different sorts of transportation choices. As we saw in our example of the city that built the light rail line, the quickly developing neighborhood at the end of the line induced high ridership on the light rail route and ultimately made using the system more burdensome for its users, who experienced crowding and long dwell times at stations as passengers boarded. Changing land use in the neighborhood, as a result, had an impact on the accessibility of the transportation system. Land-use patterns can also affect transportation networks directly by impacting the location of needed infrastructure, production facilities, materials extraction and processing (e.g., lithium for electric vehicles), user-facing support services, and back-office services (e.g., app-based ride hailing).

Consider another example. A neighborhood originally built to meet the needs of a largely car-driving population is likely to be relatively spread out, with activity centers like schools and retail out of walking distance of homes. Even if sidewalks are present in the neighborhood, it is unlikely that many people living in the area will choose to use them to commute from one area to another, as doing so would be quite a bit slower than getting around by car. In this way, then, the design of the community itself influences the choices people make to get around the community.

The transportation-land use feedback cycle is perhaps most apparent in contexts in which *past* transportation options influence the future development of neighborhoods and the transportation choices of their inhabitants. In many US cities, the neighborhoods where the densest development occurs are those adjacent to streetcar lines closed 70 years ago (Warner 1978). The arrival of a new light rail line in an existing neighborhood filled with strip malls, on the other hand, may shift few people to transit because of the ease of parking at stores in the area. This phenomenon, sometimes referred to as *hysteresis*, has important consequences, since status quo conditions are reinforced over time and difficult to challenge. A neighborhood's year of original development may often be estimated by identifying the features of its buildings and transportation infrastructure and establishing which mode of transportation was most dominant during that time (Block-Schachter and Zhao 2015). To some degree, old transportation technologies live on in the land uses of the areas that they affected.

The relationships between transportation and land use do not exist in isolation. Public policy, for one, plays a major role here. Governments, for example, can choose to invest in infrastructure designed for a certain mode of transportation. This could mean spending on new highway construction. It can also mean subsidies for or taxation of industries providing critical supplies or input for a given transportation mode, such as fossil fuel extraction or low-carbon power plant development. Local, state, or federal governments, similarly, could make regulatory choices that reduce the appeal of certain modes (such as by increasing the age required to get a driver's license or reducing the speed limit), or increase their appeal (such as by subsidizing older adults to take the bus). They could provide incentives to local businesses to use cargo bikes for local deliveries or allow delivery trucks to block parking lanes without being fined. In the case of AVs, all of these policy interventions can have indirect effects on the technology, depending on the ODD.

Governments influence land-use patterns through land-use regulations. In the United States, most zoning policy—the rules relating to allowed building size and form for new construction—is made by local governments like cities and counties (Freemark et al. 2022). These localities can choose whether to limit new housing construction to single-family homes (or allow towers). In some cases, they can make choices about whether the agricultural and natural zones surrounding urban areas are protected from development—or whether they can be used for human construction. And governments can make choices about requirements related to issues like parking requirements for new buildings. In each of these cases, local policies related to land use can affect land-use patterns over the long term, which then go on to directly affect what sorts of transportation people use.

Links between transportation and land use are informed by private sector forces, as noted in Figure 1.3. The increased accessibility offered by a new mode of transportation may have little impact on land use if a region's economy is depressed and there is little demand for new construction. The uptake of activity in a certain neighborhood may accelerate quickly, on the other hand, if a region's economy is booming. And changes may occur differently over time; a major social and economic crisis like the COVID-19 pandemic can radically alter the use of the transportation system in cities worldwide.

Private sector forces, too, can influence the public sector. Wealthy private companies have been known to lobby for the needs of their preferred investment type. Companies have been able to successfully promote their goals by promising employment of one type or another. And powerful residents can influence outcomes, too. Homeowners focused on preventing new development have historically been able to prevent the construction of housing projects—and they can also stand in the way of transportation investments (Lo and Freemark 2022).

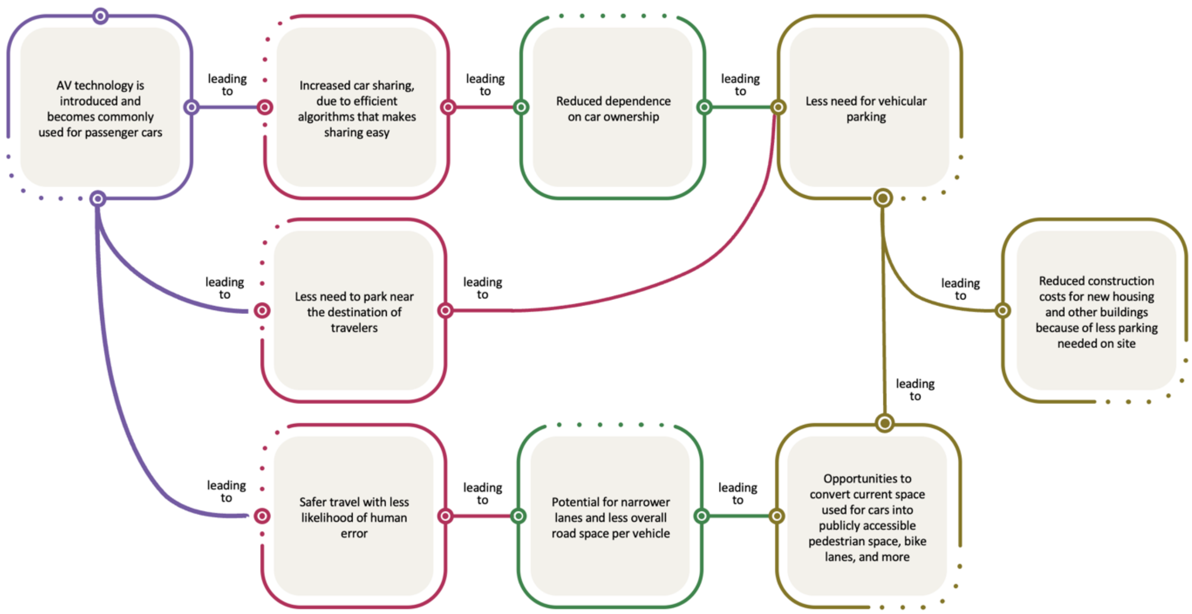
The ways by which transportation, land use, public choices, and private forces interact is mediated by varying contexts. Different sorts of neighborhoods, cities, or regions might respond to the same technologies differently; in some places, a new light rail line could spur construction, while in others it may have limited effect. The interaction between the concepts may also be influenced by political perspectives. A community whose residents and public officials focus on maximizing accessibility for people with low incomes might have different outcomes than one where the need for speed is the dominant point of view, or where keeping out people with lower incomes is a local priority. This framework is not specific to AVs, but it is suggestive of how a technology could change the built environment and be influenced by the built environment.

How might AVs and land use interact?

The example we provided of a light rail line could apply similarly across multiple types of transportation technologies. Consider how AVs could theoretically interact with land use, downstream of how AVs impact the overall transportation system. First, some scholars predict that AVs could reduce car ownership, mainly because their more efficient algorithms could facilitate car sharing (although this did not occur with ride hailing) (Cohen and Hopkins 2019; Grush and Niles 2016; Othman 2022; Zhang 2017). AVs may also reduce parking demand. They will still need to park somewhere when not in use, but they could park themselves father from crowded areas. One estimate points to up to 60 percent of parking area being freed-from this change, and a reduction in the cost of developing multifamily housing by 20 to 25 percent due to not having to include as many parking spaces (Riggs, Appleyard, and Johnson 2020).[3]

AVs may also free up urban space through more efficient road use. Roads are designed to account for human error, but AVs could—in theory—drive safely in narrower lanes and stay closer to other vehicles, reducing traffic congestion and the need for road space (Friedrich 2016; Securing America's Future Energy 2018; Wagner 2016). Congestion could also be ameliorated by AVs thanks to their built-in traffic monitoring systems (Atiyeh 2012). The public space that was previously dedicated to parking or driving could be used for a myriad of purposes, such as transit or bike lanes, expanded sidewalks, parklets, retail, or restaurants. This land could also be used for housing, increasing the size or number of residential units per lot. We illustrate these potential relationships in Figure A.2.

Figure A.2 AV technology could produce a series of cascading impacts on land use



Source: The authors.

The changes noted above could benefit society, enabling car-centric spaces to be converted to more productive uses. But the effects of AVs are far from certain. For instance, AVs may not lead to increased car sharing, since that did not occur widely with human-driven ride-hailed vehicles even though many companies tried to promote it in 2010s. Another consistent prediction in the scholarly literature is that AVs will increase VMT, even with traffic monitoring systems and a shrinking overall number of cars (Burns et al. 2012; Fagnant and Kockelman 2015; International Transport Forum 2015). This outcome could result from a combination of several factors:

- **Reduced travel costs:** AVs may reduce taxi or freight labor costs, increasing use, either through shifts from other modes or induced demand (trips that would not have otherwise occurred). The reduction in labor costs could be passed on to riders, but it may not be, depending on the competitive positioning of AV services compared to other modes of transportation, and whether AV providers operate as an oligopoly in the markets where they operate.

- **Increased convenience:** In AVs, all passengers can spend time doing other things than driving while traveling, such as working, relaxing, or even sleeping. This could encourage people to travel more often or over longer distances, at least compared to human-driven cars (since these options are already available with public transport).

- **Induced demand:** More road efficiency and reduced congestion (as explained before) could induce demand for travel in private vehicles.

- **Empty vehicle miles:** Because they do not require human drivers, AVs may also travel without passengers to pick up riders (or goods), which could add to VMT.

The first three of these factors could increase tolerance for longer trips, motivating people or businesses to locate further from urban centers to lower their land costs. This could increase the population in outer suburbs and rural regions (Gelauff et al. 2017; Kim et al. 2015; Meyer et al. 2017). One model estimates that AV service could lead to a 4 percent population reduction in inner cities and a

3 percent population increase in outer suburbs (Thakur et al. 2016). Some effects may impact groups of people differently. Zhang (2017) predicts that younger households are more likely to relocate from central business districts to capitalize on reduced housing costs, while older households may relocate closer to city centers to avoid longer waiting times for an AV to pick them up in suburban areas.

AVs may also impact land uses along commercial corridors. By reducing transportation labor costs, AVs could make product delivery more cost-competitive against brick-and-mortar retail, increasing real-estate vacancies along commercial corridors. This could extend the trends already experienced with the rise of online shopping. The research or modeling of such impacts on commercial or industrial space, however, is less developed than the other research presented here.

Space will be required for the relocation of parking. As we noted, scholars consistently project that AVs could reduce parking needs, not only because of reduced vehicle ownership but also because at destinations, cars will not need to stay (as) close to riders (Litman 2020; Stein 2021). AVs will still need to be stored and charged somewhere, but this could happen father from urban centers where land is cheaper. Conversely, existing parking garages may be transformed for new uses. Zoning—the rules relating to allowed building size and form for new construction—and governmental funding could influence that transformation (Stein 2020).

Relatedly, the current architecture of residential and office buildings—and the streets surrounding them—are often designed to provide parking. Many people arrive to buildings in cars, access parking garages, park vehicles, and reach destinations via elevators. AVs may require more drop-off and pick-up areas, but less parking. Current zoning regulations and building codes may limit how efficiently large numbers of AVs could pick up and drop off passengers (Riggs, Appleyard, and Johnson, 2020; Stein 2020).

Finally, the link between transportation and land use may also operate in the other direction: land uses may influence AV rollout. Land use will determine the availability of space for needed AV infrastructure and technology, such as communication networks, which require equipment like cameras, radars, and lidar sensors, and which may be located on roads and other public urban spaces (Liu et al 2019; Stein 2021).

Furthermore, in the context of the fast rollout of electric vehicles, most companies investing in AVs have implied that their products will be electric.[4] This means that the infrastructure needed for AVs will be inextricably linked to that of electric vehicles, including the location of charging stations, or even electrified roads that charge vehicles while driving.[5]

Road design, combined with public investment in new infrastructure, may affect how easily and quickly AVs roll out in certain communities. In particular, Liu et al. (2019) predict that AVs will operate more efficiently in communities with many roundabouts, since AV traffic could merge efficiently, with shorter queueing times (Godsmark et al. 2015). Land use may also affect the location of facilities for storing the routers and servers that AVs run on (Sudhakar 2023).

In all cases, existing land uses—including the demographic and spatial patterns of where people live and work in a community—are likely to influence the popularity of AVs and the form of AVs that predominate. And the way in which AVs roll out is likely to influence existing land uses. AV buses may be more prevalent in urban than rural areas; the availability of those buses may encourage more urbanization. Denser areas that already have more e-commerce and food delivery because of the short distance from stores and restaurants to homes may feature a higher share of AV trips for local freight distribution. Suburbs and exurbs may see more land dedicated to server farms and freight distribution, and at the same time they may see increased development pressure if people and jobs move towards suburban and exurban locales. City centers may see new land open up for parks, housing, and other uses, but they may also experience the loss of people and jobs.

These outcomes will be affected by local economic circumstances. Communities with a dynamic economy may attract substantial investment in AV freight-delivery services. Others, with less local buying power, may struggle to bring in options for riders like ride-hailed AVs. Moreover, perhaps most importantly, the ways that leaders prepare for the AV ecosystem will affect these outcomes, the issue to which we turn in the next section.

In all cases, existing land uses are likely to influence the popularity of AVs, as informed by the concept of *hysteresis,* or a lag between input and output in a system upon a change. *Hysteresis* can occur through, for example, buildings designed in the areas right around streetcar stops continuing to be used even in the period after streetcar service stops. The form of AVs that predominate in certain areas would be impacted as well. For example, AV buses may be more prevalent in urban than rural areas; denser land uses make these vehicles more useful therein. Denser areas that already feature more e-commerce and food delivery because of the convenience of traveling from stores and restaurants to homes, similarly, may have a higher share of AV trips that are for local freight distribution.

We summarize the links between AVs and land uses, based on typological characteristics, in Table A.1.

Table A.1 Potential Impacts of AVs based on Typology Characteristics

Community type		***Impacts, with an emphasis on land use in the context of attempting to achieve equity and sustainability***				
		Car ownership	**Car use**	**Capacity to change built environment**	**Residential movement**	**Freight**
DENSITY	**High Density**	If AVs boost the use of ride hailing or car sharing, they could lead to a moderate decline in car ownership, which in turn could translate to reduced needs for off-street residential, off-street commercial, and on-street parking (Cohen and Hopkins 2019; Grush and Niles 2016; Othman 2022; Zhang 2017). Reduced parking need could provoke opportunities for development.	Due to convenience and reduced travel costs resulting from AVs, people may travel more, whether they own these vehicles or use them through ride hailing (which also incurs empty miles) (Burns et al 2012; Fagnant and Kockelman 2015; International Transport Forum 2015). An increase in VMT could result in increased emissions and reduced environmental sustainability. But in very dense communities, shorter travel distances may limit the increase in VMT. Easy access to AVs may mean substitution of transit use with AV travel, though this trend could be counterbalanced if transit systems were automated as well. More VMT may impact land use by increasing the need for motor vehicle infrastructure, though not necessarily parking. AV use may encourage introduction of pick up/drop off (PUDO) zones around buildings.	Very dense communities will likely have limited availability of space to develop new infrastructure in response to AV introduction, so most changes would need to occur in already developed spaces, either through retrofitting or demolishment, which is a relatively more expensive process. However, if AVs reduce the need for parking and/or induce residents to move out of the urban cores, this could free space for new infrastructure. At the same time, if AVs improve quality of life in urban cores (such as by improving street safety and reducing traffic), they may encourage additional density in urban areas. Developers may choose to reconfigure parcels to relocate and resize parking, especially with public sector encouragement.	Due to convenience and reduced travel costs resulting from AVs, residents of high-density communities may choose to move farther away from city centers in search of more affordable housing options and amenities (Gelauff et al. 2017; Kim et al. 2015; Meyer et al. 2017). This outward movement could reduce opportunities for people with low incomes without access to AVs. However, if cities or communities manage to leverage new opportunities enabled by these vehicles to produce more affordable housing, for example by eliminating parking requirements (Riggs, Appleyard, and Johnson 2020), and/or improve the provision of urban amenities such as green spaces, the sprawling process could be partially contained or reversed through increased densification and expanded travel options for people using ride-hailed AVs. Similarly, increased access to urban destinations could encourage greater desirability of living in urban cores without the need to own a car.	Very dense cities might face challenges in allocating dedicated freight lanes or loading/unloading zones for AVs due to limited space available. However, if these vehicles lead to reduced need for on-street parking, this could free up space for formal loading and unloading zones. In very dense communities, new opportunities may become available for small-scale freight cargo distribution hubs from which small freight robots can distribute goods; this could raise new questions about the use of sidewalks or bike lanes for these vehicles, which may require these spaces to be expanded. The ability for automated freight to be delivered at night may reduce daytime street traffic, which could mean reduced congestion and thus an opportunity to reduce travel lanes.

Community type	*Impacts, with an emphasis on land use in the context of attempting to achieve equity and sustainability*				
	Car ownership	**Car use**	**Capacity to change built environment**	**Residential movement**	**Freight**
Medium Density	In moderately dense communities, AVs could make it easier to share car ownership between different households or boost the use of ride hailing, thus reducing car ownership (Cohen and Hopkins 2019; Grush and Niles 2016; Othman 2022; Zhang 2017; Wu, Cao, and Douma 2021). In addition, AVs could make it possible for families to reduce the number of cars they use. However, the impacts are likely to be less consequential than in very dense communities.	The same factors described in the high-density communities could lead to an increase in VMT, but in communities where distances between destinations are longer, there could be a more significant increase of VMT. In communities with moderate density, AVs may also discourage investments in new public transit projects (where these are already often a tough sale due to inadequate ridership to justify investment costs), so a scenario where better transit may counterbalance the convenience of AVs is less likely than in very dense areas. Higher VMT could necessitate increased motor vehicle infrastructure, which could have negative environmental impacts on the affected communities.	These communities would likely have more space availability for new infrastructure, such as parking garages specialized for AVs (Catapult transport systems 2017), or infrastructure related to autonomous public transit systems (Wu, Cao, and Douma 2021). Medium density areas may serve as important service areas for very dense neighborhoods, since they are typically adjacent to one another.	These communities may see an outflow movement of residents given the same factors described for highly dense cities considering that some of these communities may experience equal or higher housing costs than city centers; that said, this is highly dependent on local demand and population growth pressures. These communities may also be receptors of people moving out of city centers, enabled by the convenience of AVs. At the same time, given that many medium-density, suburban communities have tight land-use regulations inhibiting new construction, this increase in demand may take the form of gentrification and *reduced* population as higher-income individuals choose to live in such areas and take up more housing space per capita. Overall, the net impact of AVs on resident movement into these communities is unclear.	Road reconfiguration for AV lanes or freight delivery zones may be needed, but to a lesser degree compared to highly dense cities. Medium sized automated freight delivery vehicles may be most common in these sorts of communities. Developers may reconfigure buildings to allow for AV freight deliveries, including through different parking arrangements.

Community type		Impacts, with an emphasis on land use in the context of attempting to achieve equity and sustainability				
		Car ownership	**Car use**	**Capacity to change built environment**	**Residential movement**	**Freight**
	Low Density	The presence or use of ride hailing in low-density or rural communities is currently limited, and AVs are unlikely to change rates of car ownership due to this reason. However, the added convenience of AVs could still lead to an increase in car ownership.	Since shared AV rollout would likely be more limited in these communities, their impact on VMT levels would also be limited. It is likely that, even if people switch to AVs, their travel needs and patterns would be similar as they experience today with human-driven cars. A few people in these communities that cannot drive may start using them, adding modestly to VMT.	The availability of land for new AV-related infrastructure would be highest here, but the need for it would be limited. If on the edge of growing regions, these areas could be prime ground for the development of new automated distribution centers. AVs are unlikely to change the form of buildings, such as to encourage PUDO facilities, given the excess of space available.	These communities could be receptors of residents moving out of city centers or even moderately dense suburbs, adding to community development needs. However, the degree to which they attract more residents is unlikely to be significantly impacted by the arrival of AVs unless they are in reasonable distance of areas with services and employment.	Because of space and land availability, these communities may see an increase in the development of infrastructure for freight, such as loading and unloading areas, railyards, etc. However, because of the automation of freight systems, the development of these facilities may not be accompanied by large numbers of jobs.
DEVELOPMENT PRESSURE	**High Pressure**	AVs may become more popular and prevalent in these communities due to the ability of local residents to afford their use, thus potentially increasing car ownership and potentially the need for parking (at least on the outskirts of popular development areas). However, if high-income residents decide to opt for ride hailing services, this increase in ownership could be contained.	AVs may become more popular and prevalent in these communities, thus increasing VMT, either from privately owned vehicles or by using more automation-enabled ride hailing, thus increasing demand for vehicle infrastructure. This may, in turn, produce more pollution, which could have negative impacts on environmental sustainability.	Growing and in-demand communities often have more financial resources available due to increased tax revenue from a growing population and a thriving economy. This can enable them to invest in AV infrastructure development (OTFAV 2019). The form this infrastructure takes, however, is likely to vary substantially between communities based on local preferences. AVs may encourage the reconfiguration of parking lots or buildings themselves to accommodate residents and freight users that are more apt to use AV technologies for day-to-day needs.	Due to increased demand, growing cities will likely see rises in the cost of living, mainly in terms of housing, which will accelerate pressure for residents who are unable to afford these higher costs to leverage the convenience of automated vehicles to move out farther away from city centers in search of more affordable lifestyles (Gelauff et al. 2017; Kim et al. 2015; Meyer et al. 2017). If AVs improve quality of life in high-pressure communities, this increased demand could encourage more dense development in such areas (if local land-use rules enable it). But higher costs could also, as noted, encourage further movement outward. We thus might expect AVs to encourage both infill and exurban growth patterns.	Growing cities will likely experience higher demand for goods and services, leading to increased freight needs. AVs could help meet this demand more efficiently by encouraging route optimization, reducing congestion, and providing continuous delivery services. Urban growth may encourage the creation of exurban sprawl of distribution centers. High-pressure cities may see a reduction in employment in these industries and the possibility to redevelop land that they currently occupy.

Community type		Impacts, with an emphasis on land use in the context of attempting to achieve equity and sustainability				
		Car ownership	**Car use**	**Capacity to change built environment**	**Residential movement**	**Freight**
	Low Pressure	In these communities the rollout of AV technology could be more limited (and/or have a less substantial impact on overall driving patterns), thus car ownership rates would not be dramatically affected. We expect that there would be less initiative by private companies to provide new services in such communities, which could contribute to this outcome.	In these communities, the rollout of AV technology could be more limited, thus VMT would not be dramatically affected.	Stable or declining cities may have limited financial resources due to a stagnant or shrinking tax base. This can hinder their ability to invest in new infrastructure, including AV-related projects (OTFAV 2019). On the other hand, this fiscal condition may encourage them to seek out more private investment in greenfield automated distribution centers and automated vehicle maintenance areas. This is particularly likely to occur if low-pressure communities are located adjacent to high-pressure areas, where there is more substantial demand for the use of AVs. AV technology in this context is unlikely to impact building design and form given the limited demand for new construction.	AVs may still provide options for residents looking to lower their housing costs to move away from expensive areas, but since demand for housing in these communities is already lower, this sprawling effect would be expected to be limited compared to within growing communities.	There could be efforts to revitalize declining areas by supporting efforts to attract employment in the automated freight technology sector, but these communities might have fewer financial resources available for AV-related investments, hindering their ability to adopt new technology and upgrade infrastructure.

Community type		*Impacts, with an emphasis on land use in the context of attempting to achieve equity and sustainability*				
		Car ownership	**Car use**	**Capacity to change built environment**	**Residential movement**	**Freight**
CAR AND TRUCK RELIANCE	**High Car and Truck Reliance**	If AVs increase the convenience and use of ride hailing services or shared car ownership, they may lead to a decline in car ownership (Cohen and Hopkins 2019; Grush and Niles 2016; Othman 2022; Zhang 2017; Wu, Cao, and Douma 2021). However, absent these conditions, communities whose residents are already highly reliant on cars for their trips could simply swap their regular vehicles for AVs, thus maintaining current rates of car ownership. Depending on the local situation, this may result in parking needs being maintained over time.	In communities with already high rates of car use, the introduction of AVs could further increase VMT given the higher convenience and lower costs inherent in these vehicles (Burns et al 2012; Fagnant and Kockelman 2015; International Transport Forum 2015). Automated ride hailing may also increase VMT through empty vehicle miles.	Adapting existing infrastructure for AVs may be more complex in car-dependent cities. Retrofitting roads, parking structures, and signage to accommodate AVs could be disruptive and costly for a community full of drivers. On the other hand, the promise of reduced congestion in the context of AVs could encourage residents to tolerate infrastructure changes (Friedrich 2016; Securing America's Future Energy (SAFE) 2018; Wagner 2016). Because of the continued use of privately owned cars, these communities are unlikely to experience major changes in building design to accommodate different AV needs.	The potential sprawling effects resulting from the introduction of AVs described above could be augmented by the availability, and in many cases oversupply, of car infrastructure. In other words, residents of a community with many highway lane miles could more easily move out of urban cores to leverage the increased convenience of AVs for commuting long distances.	AVs could boost the freight industry by filling potential gaps in the availability of drivers and creating efficiencies that leverage the existing truckload freight infrastructure. Automated freight could encourage the development of smaller-scale freight delivery programs, which could mean less truck reliance and replacement with small-scale robot deliveries.

Community type		*Impacts, with an emphasis on land use in the context of attempting to achieve equity and sustainability*				
		Car ownership	**Car use**	**Capacity to change built environment**	**Residential movement**	**Freight**
	Low Car and Truck Reliance	These communities could see an increase in car ownership if the introduction of AVs displaces the use of alternative modes of transportation due to their competitive convenience. On the other hand, automated technology could be used to improve transit systems and that way contain a potential increase in car ownership (Wu, Cao, and Douma 2021). AVs could also increase the use of ride hailing services and thus reduce ownership among the smaller share of people who may currently be owning cars in these communities (Cohen and Hopkins 2019; Grush and Niles 2016; Othman 2022; Zhang 2017).	These communities could see an increase in VMT due to the competitive convenience and lower travel costs potentially offered by AVs, either because individuals use more of their own cars or use ride-hailing services more heavily, substituting for walking, biking, and transit trips (Burns et al 2012; Fagnant and Kockelman 2015; International Transport Forum 2015). But automated technology could also help improve transit services, thus offer better alternatives to car trips in places where people are already accustomed to alternative modes of transportation (Wu, Cao, and Douma 2021).	These communities might have more flexibility in planning and adapting their infrastructure for AVs, as there is less pressure to accommodate high car traffic. They may be better capable of replacing parking structures and lots with other uses and may be more apt to convert streets to allow for a variety of users. These areas might see substantial changes in the street front to accommodate PUDO offerings. They may also be subject to substantial changes in building design to encourage higher use of AV freight options, particularly small-scale vehicles.	The potential sprawling effect of AVs would likely be more limited compared to communities that are more highly reliant on cars due to these communities having better transit alternatives and fewer options to drive. They may be able to leverage automated vehicles to improve quality of life within their communities (such as through less pollution, safer streets, and even carless streets) to encourage more growth in communities where cars and trucks do not dominate.	Communities with lower demand for truck freight might have less immediate incentive to invest in automated truck freight, potentially delaying adoption. They may leverage automated technology to boost other ways to move products and services, such as through delivery robots and bike carriers.

Why does public policy matter when it comes to AVs and land use?

Public action is important not only to achieve a higher quality of life through transportation infrastructure, but also to prevent new transportation technologies from negatively impacting equity and environmental sustainability. Technology is not inherently good or bad; its impact depends on how it is used. Policy can make the difference between AVs having positive or negative impacts on society and the environment, and in many cases, policies can set off a chain of path dependencies. Proactive planning and policymaking is essential to ensure that the AV ecosystem helps communities achieve their goals.

There are a few key ways that public policy can influence the AV ecosystem and the AV-land use connection. Governments can choose to invest in infrastructure designed for a certain mode of transportation. This could mean spending on new highway construction or on public transit (which could, respectively, mean more car-sized AV use, or more automated buses). Governments could subsidize or tax industries that provide critical inputs for a given transportation mode, such as fossil fuel extraction, or low-carbon power plant development (which could, respectively, mean more or less transportation-related emissions).

Local, state, or federal governments, moreover, could make regulatory choices that reduce the appeal of certain modes (such as by increasing the age required to get a driver's license or reducing the speed limit, both of which would make using a personal car less useful), or increase the appeal of other modes (such as by subsidizing older adults individuals to take the bus). They could provide incentives to local businesses to use small automated robots for local deliveries or, in contrast, allow large delivery trucks to block parking lanes without being fined. In the case of AVs, all of these policy interventions could have indirect effects on the rollout of the technology. Consider this example of a path dependency: A policy that expands availability of car parking could increase the ease of driving; this could, in turn, reduce transit ridership. Reduced ridership could deprive the local transit agency of funding, forcing it to reduce service; this, in turn, could encourage more driving.

Governments influence land-use patterns through land-use regulations. In the United States, most zoning policy is made by local governments like cities and counties (Freemark et al. 2022). These localities can choose, for instance, whether to limit new housing construction to single-family homes or to allow towers, or whether to allow new development on the agricultural and natural zones surrounding urban areas. They can also make choices about requirements like minimum parking for new buildings. In each of these cases, local policies related to land use can affect land-use patterns over the long term, which then directly affect what sorts of transportation people use.

Policy is also influential in shaping the link between transportation and land use. Policymakers determine whether to allow for the widespread adoption of new technologies (e.g., in the face of safety risks), choose whether to subsidize their use (e.g., by using tax dollars to fund infrastructure), and implement associated regulations (e.g., by mandating parking requirements for new building construction). These choices can be contested and are often subject to disagreement and revisions throughout the lifecycle of a given technology.

State of the practice: public sector efforts to link land use and AVs

Expert predictions and modeling exercises suggest that the impacts of AVs on land use and zoning, and vice versa, could go in many different directions. Ultimately, the direction in which this new technology takes us depends to a large degree on government or public action. The transportation-land use feedback cycle explained earlier will offer many iterations for public entities to shape how AVs impact the urban form, not only by regulating the technology itself, but also by establishing the rules and guidelines by which the built environment may adapt to AVs. Public action may determine whether AVs lead to higher levels of road use and sprawl, or to denser, more sustainable cities.

In this section, we begin by providing a framework for what it might mean for public policies to engage on this link, since choices made by governmental agencies can play a major role in impacting technological rollout (we detail those choices through examples in the historical case studies, below). So far, because of the newness of AV technology, there have been limited public efforts to link land use outcomes with AVs.

A framework for leveraging public policies to link transportation and land use

One fundamental question is the degree to which public policies may influence the changes we noted above, including increased access to certain destinations, longer trips, altered modal choices, modified building designs, and variations in neighborhood design. None of these outcomes is preordained by the AV technological change. Governments could undertake one or more of the policies in Table A.2.

Table A.2 Potential Approaches to Public AV Regulation

Approach	Examples
Approaches that could encourage AV use	
Directly subsidize AV use	▪ Subsidies for AV service use (e.g., fare assistance or private AV purchase) ▪ Subsidies for AV technology companies in technological development ▪ Investments in improved AV infrastructure (e.g., connected vehicle technology or parking lots for AVs)
Indirectly subsidize AV use	▪ Investments in improved road infrastructure (instead of other modes) ▪ Subsidies for household or business transportation electrification ▪ Undertaxing AV externalities (e.g., related to air pollution and sprawl)
Pro-road use policies	▪ Increasing speed limits ▪ Reducing obstacles to AV use (e.g., allowing young people to travel unaccompanied) ▪ Dedicating rights-of-way to AV use exclusively ▪ Mandating low standards for AV safety
Pro-road building or land-use policies	▪ Minimum roadway access requirements for buildings ▪ Limitations on building density
Approaches that could discourage AV use	
Tax AV use	▪ Taxing sale of privately owned AVs ▪ Per-ride fees on ride-hailed AV use (e.g., for single-occupant trips) ▪ Taxing infrastructure related to AV use
Subsidize other modes	▪ Invest in transit, bicycling, and pedestrian improvements ▪ Reducing roadway rights-of-way in favor of other modes
Anti-road use policies	▪ Reducing speed limits ▪ Increasing obstacles to AV use (e.g., high insurance requirements, implementing fees for roadway use) ▪ Preventing AVs from using certain rights-of-way ▪ Mandating high standards for AV safety

Approach	Examples
Anti-road building or land-use policies	▪ Reducing road access rules for buildings (e.g., eliminating curb cut or driveway allowances or requirements) ▪ Encouraging higher development densities and increased use mix

Other potential policies could impact aspects of AV technology. For example, some governments may desire promoting shared use of AVs and thus choose to provide subsidies explicitly for that purpose. Others might develop rules specifically related to freight-carrying AVs operating on sidewalks. Some policies may benefit some forms of AVs and not others. Many of the policies listed in table A.2 are equally relevant to the existing, driver-operated roadway system as to future AVs. Even so, in general, each policy approach could be applied broadly to both passenger and freight AVs. Policies encouraging AV use may, collectively, result in the changes in outcomes we listed above, such encouraging longer trips. These may go on to impact land use and the built environment.

In theory, a multitude of governmental entities may be involved in AV policymaking. In the United States, local, metropolitan, state, and federal governments each have some jurisdiction over aspects of these issues. For example, localities often manage land-use rules through zoning; metropolitan governments distribute transportation funds through metropolitan planning organizations, states make rules about vehicle licensing, and the federal government raises a large share of dollars for new infrastructure. Because of jurisdictional fragmentation that is common throughout the country, many different agencies are involved simultaneously in managing the roadway. For example, in Fairfax, Virginia, eight different units of government have ownership over elements of the roadway system.[6]

Each of these entities may promote different policies, following different ideological priorities about what outcomes to encourage. Some governments and agencies may choose to allocate more roadway space to AVs, for example, while others may leverage the potential efficiency of these vehicles to allocate more space to pedestrians and cyclists. Some may provide financial support for AV ownership—whereas others may focus their investments on transit fare discounts.

The state of the practice thus far

To what degree have policymakers taken steps thus far to respond to AVs in the context of land use? In recent research (Freemark et al. 2022), our team conducted a nationwide examination of how federal and state governments are planning for AVs. This work focused largely on regulations directly related to AVs—from vehicle design to vehicle operations, consumer standards, and street standards—with less of an emphasis on indirect impacts of the technology, such as relating to land use. Nevertheless, the research is revealing of the limited engagement on this issue.

First, the US Congress has not passed any AV-specific law, though there have been attempts to do so over the past few years (Freemark et al. 2022). The National Highway Traffic Safety Administration (NHTSA) has taken steps to monitor AV performance. NHTSA, for example, currently requires manufacturers and operators to report crashes involving level 2–5 AVs under a standing general order.[7] NHTSA has also developed measures to counter potential cybersecurity risks. But the US government has not developed guidelines for AV design, and, as of this writing, continues to require automakers to ask for exceptions to federal crashworthiness and design standards for AVs with unconventional designs (e.g., without steering wheels). Other policies at the federal level could indirectly impact AVs (e.g., by requiring all new vehicles to be electric, as has California[8]), radio frequency liberalization (e.g., recent decisions by federal regulators on the 5.9 GHz spectrum that had been reserved only for smart vehicle technology),[9] or data privacy regulations. The latter will be critical to how AV providers will be able to learn from travel patterns and improve their operations.

As of this writing, a minority of states have passed legislation directly related to AVs (table A.3; sourced from Freemark et al. 2022). In general, states that have passed laws focus their efforts on studying the vehicles, whether through developing committees or allowing for their testing. But in our investigation, we identified zero states that have passed legislation specifically linking AVs to land-use policy or road access requirements. In other words, there is considerable evidence that states have not yet taken much of a step towards planning for this technology. Though California has developed a regulatory regime related to AVs through its Public Utilities Commission (e.g., by requiring AV operators to apply for permits and provide data about trip origin and destinations; see California Public Utilities Commission 2020), this approach keeps land-use issues at a distance.

Table A.3 Frequency of State Legislation Related to AVs, by Theme

Themes	Share of all states with laws in this thematic area
Funding to research or test AVs	4%
Crash reporting	8%
Committees related to AVs	27%
Land use	0%
Liability rules	22%
Registration and permitting	20%
Ride hailing	14%
Road access	0%
Studying AVs	24%
Taxes and fees specifically for AVs	8%
Testing AVs	31%

Source: Freemark et al. 2022, based on review of 122 laws passed by states as of July 20, 2022.
Notes: Counts District of Columbia as a state.

We were unable to identify examples of local governments implementing ordinances or regulations intended to directly link AVs and land use (Freemark et al. 2022), except for an executive ordinance in Pittsburgh with directions for the local Department of Mobility and Infrastructure to develop and publish policy recommendations.[10] Comprehensive examinations of local government and metropolitan planning organization plans shows that they had committed few resources to planning to AV rollout (Freemark, Hudson, and Zhao 2019; Guerra 2016), though, as we show below, that is increasingly not true for many of the nation's states and cities. One issue is that local governments lack the resources to plan for a technology whose parameters have yet to be fully developed.

Even so, many local governments do want to plan for AVs in the context of land use. In a representative survey of US local planners, Freemark, Hudson, and Zhao (2020) make several findings:

- A plurality of planners agree that municipal governments should develop regulations related to AVs that reduce sprawling land uses (51.3 percent of respondents agreeing versus 19.5 percent disagreeing), increase street space for pedestrians (70.5 percent versus 7.7 percent), increase access to mobility for low-income people (51.6 percent versus 26.4 percent), and increase public transportation ridership (47.7 percent versus 28.4 percent).

- A minority of planners agree that municipalities should develop regulations related to AVs that would reduce vehicle miles traveled (26.5 percent versus 50.3 percent) or reduce private car ownership (16.2 percent versus 69.4 percent).

- Most planners personally think it is a good idea to reduce minimum parking requirements for new developments (87.2 percent), transform car lanes into space for pedestrians and cyclists (79.9 percent), and implement road pricing (74.1 percent). But they raised questions about the legal, bureaucratic, and political support for executing such policies.

We searched for localities and states that have—in the years since the studies noted above—developed plans specifically related to the AV ecosystem. We identified a cohort of several key plans that integrate elements related to land-use planning.

Los Angeles, for example, recently developed a strategic AV plan (Los Angeles Department of Transportation 2018). The plan specifies the city's focus on promoting "an electric, shared, active, and autonomous mobility system that tackles congestion, enables economic development, provides equitable services, and saves lives" (pg. 1). It notes that "the City must set the ground rules for private mobility providers to operate on our streets" (pg. 5). That said, the plan does not detail how the department of transportation, for which the plan is designed, would influence land use-related outcomes, since that remains within the jurisdiction of another city agency.

The City of Austin (2017), too, has laid out a plan for responding to AV technology with a land-use component. The plan notes that AVs "have the potential to encourage individuals and households to move further away from the city center under the assumption that long drive times can be used for work or entertainment purposes" (pg. 10). The city recommends "bold land use policies" to "encourage densification and discourage single-occupancy commuting options" (pg. 10). That said, the plan is not specific about how to do so; rather, the city "should pursue a collaborative process across disciplines, city and regional partner systems" (pg. 11) to reduce parking requirements, better manage curb space, and adapt parking garages for future uses (pg. 12). The City of Pittsburgh (2023) similarly argues for using AVs to "promot[e] and enabl[e] land development patterns that locate everyday destinations and needs in close physical proximity to people," but does not specify how to achieve that goal.

The City of Seattle's (2017) mobility plan also emphasizes that the city "must shape how automated mobility impacts and benefits our citizens," with the goal of asking and answering "what do we want our city to look like?" (Appendix C, pg. 2). Seattle's plan, more specific than those of Austin, Los Angeles, or Pittsburgh, emphasizes that the rise of AVs should not disrupt the city's goal of supporting walking, biking, and transit; the plan recommends developing regulations that prioritize the use of limited right-of-way space (pg. 5). Seattle's plan includes some policy proposals that could impact land use, such as creating geofenced districts and corridors, and implementing time-based access restrictions or pricing. Finally, the plan points to land use, noting that key policy goals should be "ensur[ing] automated vehicles advance our land use goals and capture the value of transit-oriented development," and "requir[ing] future development and building standards to be future compatible, reflecting advances in shared automated mobility," including through new forms of vehicles (pg. 10). The plan lists possible zoning changes that the city had not yet implemented:

- Requiring new parking to be reusable for other uses and furnished with charging facilities;
- Phasing out off-street parking requirements (with savings directed to affordable housing and transportation demand management strategies); and
- Integrating street and aerial drone delivery systems into building design and operations

Washington, DC's Autonomous Vehicles Working Group (2020) developed recommendations related to land-use policy. The plan notes that AVs could assist in absorbing some of regional transport needs. The group notes that parking is expensive, and that though "the District revised minimum parking requirements earlier this decade... the requirements... should be re-evaluated in light of AV adoption, so that parking is not constructed unnecessarily" (pg. 166). The plan also recommends a "comprehensive review of land use and zoning codes and land use policies" to address changing needs; this could address the use of gas stations, curb-side space, and automobile repair facilities (pg. 166).

Cities have not acted alone in planning. Oregon's state Task Force on Autonomous Vehicles (2019) recommends that AVs be taxed based on occupancy level, responding to the fact that AVs will only decrease congestion with shared rides and reduced vehicles on the road, but could increase it if vehicles circulate with no passengers (pg. 69). That plan notes that AVs should "support Oregon's Land Use Planning Goals, particularly housing, transportation, and urbanization goals" (pg. 72), but is not specific about how they could do so.

The Michigan Department of Transportation's (2021) plan recommends changes the state should pursue to integrate AVs into the state mobility network, mentioning land use once (pg. 80). Finally, the Minnesota Department of Transportation's (2019) AV plan notes that land use is "an area with particular susceptibility to" AV impacts (pg. 73). It does not establish a state role to direct the link between AVs and land use, instead, it recommends coordinating with local, regional, and tribal governments.

In sum, local and state governmental planning for the connection between AVs and land use remains underdeveloped. Though some governmental agencies are openly discussing the issue in planning documents, few have identified recommendations for managing that relationship. Nor could we find states or localities that have passed a law or ordinance *requiring* some specific change to respond to the AV ecosystem.

A key issue that may be inhibiting public agencies' ability to manage the AV ecosystem's impact on land-use outcomes is that the public entities for which we identified plans, separate their transportation and land-use bureaucracies. State governments largely leave land-use issues up to local governments, which are expected to take on the challenge of land-use and zoning policy even as states manage extensive departments of transportation. And even local governments separate their (land-use) planning departments from their transportation departments, making coordinating the link difficult.

Potential for public policies linking AVs and land use

A variety of non-governmental organizations have studied AV impacts and sought to recommend roles that public actors could take in planning for a future AV ecosystem. These recommendations vary in their applicability but generally are designed to describe a fully automated AV environment.

We reviewed planning reports that evaluate the links between land use and transportation, and that propose ideas about how to respond to them. We organize these concepts in terms of theme for intervention in Table A.4, but do not assess their viability or desirability (nor their potential implementability in different sorts of community contexts). Many of the concepts described here have been proposed by those working in transportation policy, even outside of the AV context (Schwartz 2015). Many planners and policymakers envision AVs as a mechanism to achieve goals that they already had in mind for the future of their respective communities.

Table A.4 Potential approaches to public AV regulation in previous policy recommendations

Approach	Planning Concepts
Collecting data for scenario planning	▪ Several reports emphasize collecting data from AV services, such as in terms of the number of trips taken from one location to another, both for freight and passenger uses. ▪ Collecting data would enable planners to identify how AVs encourage changing travel patterns and produce outcomes such as induced demand or exurban commuting. ▪ Data could be leveraged for scenario planning to produce better models.
Road efficiency for positive environmental outcomes	▪ Because AVs theoretically increase roadway efficiency, several reports noted the opportunity to leverage AVs to stop road expansion. ▪ Others noted that this provided governments an opportunity to alter standards for roadway efficiency, replacing the level of service standards used for automobiles and trucks with baseline standards for all modes, including transit, walking, and biking.
Implementing road pricing	▪ Because AVs could encourage increased travel, several reports noted that cities, states, and the federal government should consider collaborating to develop VMT fees. ▪ These fees could be scaled based on vehicle use, rewarding shared-use vehicles and discouraging the movement of empty AVs along congested streets. ▪ Others pointed to developing curbside use fees for freight and passenger service to ensure availability of drop-off areas or flex zones and minimize the problem of vehicles circling the block looking for parking and double parking.
Altering parking rules	▪ Many reports emphasized that AVs could reduce parking demand because AVs could park somewhere other than the destination of the freight or passengers, and because the ease of sharing AVs could reduce the need for parking in the first place. ▪ Reduced parking could be associated with eliminated minimum parking requirements for developments (a trend that already underway in many cities), and adjusted parking dimensional standards (because AVs are theoretically better able to fit into small spaces). ▪ One option was to develop a "cap and trade" system for parking to allow parking to be accommodated throughout an entire district, rather than allocated building-by-building. ▪ Several noted that reduced parking could be associated with redevelopment. Local governments could rezone and encourage construction on former parking lots.
Redesigning streets	▪ Many recommended leveraging AV efficiency to redesign street rights of way to prioritize transit, pedestrians, cyclists, and freight. ▪ Certain streets or neighborhoods could be geofenced for non-motorized uses. ▪ Improved AV safety could allow lower speed limits, increase pedestrian crossing areas, and reduce street lanes, in the interest of increasing pedestrian and cyclist comfort.
Expanding multi-modal access	▪ Many reports highlighted the value of encouraging links between AVs and other forms of mobility, particularly transit for long-distance trips and to reduce congestion. ▪ Mobility hubs where both passengers and goods could switch between modes could mean last-mile connections between a rail line and a small-scale AV, or distribution facilities switching goods from an AV truck to a small AV robot that can use the sidewalk.
Sprawl repair	▪ Several reports pointed to the potential to use AVs to address socially damaging elements of urban sprawl, such as reliance on cars, separation of uses, and carbon emissions. ▪ Some noted that AV technology could be associated with higher density land uses facilitated through new zoning policies. ▪ Others noted that, to stave off suburban or exurban development, AVs could be associated with new growth management strategies that prevent new construction on the edge of urban areas where agricultural or natural land is currently present.

Source: The authors, based on a review of Anderson et al. 2016; Anderson and Larco 2017; Bellinger et al. 2017; Crute et al. 2018; Henaghan 2018; Henry et al. 2017; Lewis, Rogers, and Turner 2017; National Association of City Transportation Officials 2019; Riggs, Appleyard, and Johnson 2020; Shared Use Mobility Center 2023; Speck 2020; Union of Concerned Scientists 2017.

These concepts for public sector regulations for AVs differ somewhat but share many common themes. All agree that the regulatory environment and even the shape of AVs will continue to evolve, but that policymakers should plan for their arrival; note Anderson et al. (2016: 145), "we think the guiding principle for policymakers should be that AV technology should be permitted and encouraged if and when it is superior to average human drivers." It is not yet clear when that point will occur. Henaghan

(2018: 20) agreed with authors of other reports reviewed for this project in noting that "planning must anticipate the disruptive effects of technology" and getting public policies right before it is too late is essential to be able to the leverage the benefits of AVs without reinforcing their negative attributes (Acharya and Morichi 2007).

Appendix B: Detailed historical examples

AVs could influence on land-use patterns in the cities and regions where they are deployed. As we described in our literature review, the reduced travel costs made possible by automation could encourage more driving; this could go on to spur suburban development. On the other hand, AVs could reduce the need for parking; this could encourage redevelopment of parking lots into housing or other uses. Historical examples of the land-use impacts produced by previous transportation technologies can help us understand what we might expect from AVs.

In this section, we describe our learnings from six case-study historical transformative transportation technologies. We chose technologies that:

- Have had known impacts on travel patterns and on land-use patterns;
- Have involved considerable public and private investment and elicited efforts from public entities to address impacts; and
- Have had consequences on a breadth of communities that are broadly representative of conditions throughout the United States

There are many transportation technologies that could fit those conditions. But we identified six case studies especially worthy of examination. Our list of technologies, ordered by period of rollout is:

- Streetcar technology
- Highway systems, leveraging automobile and trucking technology
- Container-based freight transportation
- Urban bicycle sharing
- App-based ride hailing, supported by smart phones
- Modern electric vehicles

For each technology, we reviewed previous scholarship on what constituted that technology's primary features and then established what we know about its relationship with land-use outcomes. We define land-use impacts broadly, incorporating land uses, streetscape, and urban design. We discuss each of these issues in the historical analyses in this section. We frame our understanding of these links within the transport–land use feedback cycle described by Bertolini (2012). It is infeasible to separate the technology from land-use outcomes, nor from the market or policy landscapes that influence the two. These conditions influence one another, and we cannot always know which came "first." Nevertheless, we consider changes and path dependencies over time. In Table B.1, we identify several key examples of how the technologies have been associated with land uses, at two different scales: In the immediate environment and in regional development patterns.

Table B.1 Example Land-Use Impacts of New Transportation Technologies Across Geographical Scales

Technology	Localized scale	Regional scale
Bicycle sharing	▪ Changes at the street and curb design level to incorporate bike docking stations and lanes	▪ No impacts identified in the literature

Technology	Localized scale	Regional scale
Freight containers	▪ End of use of historic port zones; opportunity for inner-city redevelopment ▪ Creation of truck-dominated exurban logistics zones ▪ Affirmation of large, warehouse-like retailing	▪ Displacement of transportation, industrial, and warehousing employment to suburbs ▪ Residential investments in city former port areas and suburbs
Electric vehicles	▪ Requirements for altered curb space utilization that allows for vehicle charging ▪ Incorporation of charging facilities in buildings	▪ No impacts identified in the literature
Highways	▪ Destruction of neighborhoods and conversion of residential property into highways ▪ Conversion of agricultural and natural land in suburbs and rural areas into highways ▪ Conversion of parcels near highways into commercial and industrial uses ▪ Neighborhoods separated by highways and increased development of parking spaces	▪ Suburbanization of people and businesses ▪ Population loss in central cities ▪ Loss of agricultural and natural land ▪ Decline in demand for land in rural areas that highways did not reach
Ride hailing	▪ Requirements for altered curb space utilization that allows for vehicle pick-ups and drop offs	▪ No impacts identified in the literature. Hypothetically, however, ride hailing may be contributing to the growth of secondary entertainment districts that are difficult to access by transit
Streetcars	▪ Dense development in the neighborhoods adjacent to streetcar stops	▪ Urban development on suburban fridge along streetcar lines

The scalar dimensions of land-use impacts illustrated in Table B.1 demonstrate that transportation technologies can impact the built environment in different ways, depending on the location or type of environment we are interested in. Acknowledging these multi-scalar differences will be key to understanding how AVs may impact the built environment over time.

In the following sections, we review research on the case-study transportation technologies, considering what we know about their respective associations with land-use patterns. And for each, we identify what parallels we may be able to learn from their experience to understand how AVs may be associated with land-use patterns.

Streetcars

Streetcars are transportation conveyances that travel within the public roadway right-of-way on metal railways. Most of the streetcars referenced in this example were powered by electricity via overhead catenary lines. Streetcar systems flourished in US cities of all sizes, serving as the main mode of transportation for urban residents from the late 1800s to the mid-1900s. They had a major impact on the size and form of cities. Before streetcars, the physical scope of cities was constrained by the distance someone could commute by walking (Jucha 1979). As the first large-scale transportation affordable to individuals with working class professions, streetcars enabled peri-urban areas to become "streetcar suburbs," offering housing in less densely populated settings but within commuting distance of jobs. This led to large expansions in urban land area, with less dense housing developed in patterns that closely tracked the linear extension of streetcar routes (Jucha 1979; Warner 1978; Xie and Levinson

2010). These newly developed areas then experienced higher land costs and shaped the location of future streetcar lines.

The most important parallel between streetcars and AVs is the role of indirect public subsidies. Public investment in roads and other automobile infrastructure served as an indirect subsidy for buses and private cars and was a likely accelerator of the decline of streetcar use. Likewise, the scale of AV future rollout could be determined by public sector support in the form of direct or indirect subsidies. If AV costs internalized all their externalities, including the infrastructure they operate on, they would likely struggle to compete against other (potentially subsidized) modes. Additionally, by reducing the time or burden of travel, AVs could increase suburban land development like streetcars did.

The elements of streetcar technology, and a short history

Streetcars are transportation conveyances that travel within the public roadway right-of-way on metal railways. They have been powered by a variety of propulsion systems over the course of their history. Streetcars are operated by service providers (either public or private) that allow public passenger access (usually with fares), but in rare circumstances streetcars are for private use only or used for freight. Most streetcars run on right-of-way shared with other users (such as motorists and bikers), though some have independent right-of-way that allows them to move more quickly; in rare cases, that independent right-of-way is elevated or tunneled. The difference between streetcar technology and tramway, interurban, or light rail technology is up for debate, though the latter three technologies are more likely to describe systems using independent rights-of-way and longer trains (often with more than one linked car). While they are still present in many cities across the United States, streetcar services had their heyday between the 1880s and 1930s, when they were so widespread as to be the primary means of transportation in urban areas nationwide (Graffy and Kihm 2014).

The implementation of streetcar technology in the 1800s across the United States reflected growing demand for mobility in urban areas as populations and local economies expanded. In the early part of the century, the main public transportation option in cities was the "omnibus," a horse-drawn carriage typically seating 6 to 12 passengers that shuttled passengers on pre-determined routes (Jucha 1979; Zylstra 2011). Because of the high cost operators charged to ride them, omnibuses were primarily used by higher-income residents; this limited use meant they did not exert broad influence on the size or form of cities, or the arrangement of its residents or economic activities. Zylstra (2011) notes that omnibuses lacked the cultural significance that would later be ascribed to streetcars.

Omnibuses, moreover, provided poor service because they relied on the imperfectly paved and maintained surfaces of public streets (many of which were simply dirt at the time). Beginning in New York in 1832 and expanding quickly nationwide by the 1850s, private companies began installing iron rails to smooth the ride. Cities provided franchises to private companies to implement these "horsecar" services, which could be used on streets without disrupting traffic because the rails were flush with the pavement. But these horsecars were fundamentally limited by their means of propulsion—horses—which were slow, required feeding, and were not able to carry large loads of passengers.[11]

The real mobility revolution came with the ability to leverage human-made power. At first, investors embedded cables into the street; these cables connected to traction houses where steam engines pulled them in a continuously moving loop. The first such vehicle was implemented on San Francisco's Clay Street in 1873, designed to navigate that city's hills (Prince 1979).[12] San Francisco—which by the century's end had laid more than 100 miles of cable route—became an example that other cities, hilly or not, emulated. Cable cars could travel up to 10 miles per hour (twice as fast as horsecars), and they were cleaner, quieter, and more reliable than their antecedents. By 1894, there were 360 miles of cable car lines in 29 US cities, carrying 400 million passengers a year (Middleton 1985).

But cable cars had their own problems; in particular, cables were prone to fraying and breaking. The fact that the cables were embedded under the street made them subject to weather and other impediments. A new technological advance was needed. In 1888, an electric powered streetcar—the primary subject of this section—was introduced for the first time, in Richmond, Virginia (Prince 1979). Electric streetcars were powered by overhead wires conveying electricity. The technology was reliable and could power streetcars carrying many passengers. By the end of the first decade of the 20th century, virtually all cable car lines had been replaced by electric streetcars (Middleton 1985).

Electric streetcar systems developed rapidly across the United States, being implemented in cities big and small. They became the primary means of transportation for urbanites—arguably the most important travel option for most US residents. In 1920 alone, Americans took about 14 billion streetcar rides, equivalent to more than 130 trips per capita nationwide (Graffy and Kihm 2014); by comparison, Americans took a total of 9.9 billion transit rides overall in 2019, equivalent to just 30 trips per capita.[13] At their peak, cities across the United States had more than 11,000 miles of streetcar lines, with cities like Chicago (more than 500 miles) and Los Angeles (more than 1,100 miles) leading the way.[14]

In the following decades, streetcars met their demise in most US cities, for a variety of reasons. With the rise of the automobile (and the construction of highways; see next section), many Americans simply no longer chose to travel by public transportation—especially since many of the places they wanted to go were not accessible by streetcar as suburbs sprawled. Many cities mandated that private operators charge fares too low to ensure adequate maintenance. And, as cities municipalized transit systems (due to private operators failing to remain profitable), they replaced streetcars with buses, which could travel more quickly through traffic.[15] Only a small number of streetcar systems continued service after the 1950s, before a small-scale reinvestment in streetcars in several US cities in the 2010s.

The links between streetcar technology and land use outcomes

In general, streetcars led to decreased residential density and increased separation of land uses. As the first motorized form of public transportation affordable to the working class, they enabled development in places previously inaccessible to downtown jobs. This opened up swaths of peripheral urban land to residential development; this expansion of the city's physical footprint enabled housing to be built in less dense forms, such as single-family, detached houses. While new suburban communities had some retail and local businesses, during the heyday of streetcar service, most working residents still commuted to the city center, which remained the hub of most industrial, government, and financial activity. Streetcars and land-use patterns impacted one another mutually. The existing locations of urban cores, peri-urban residential developments, and undeveloped land guided the placement of new streetcar lines. In turn, the construction of new streetcar lines precipitated the construction of developments along their length—in fact, the two were often planned in tandem. This led to new suburban hubs that then influenced the siting of future streetcar lines.

Before streetcar technologies were widely implemented, the physical scope of cities was generally constrained by the distance that a person could commute by walking (Jucha 1979). In Boston, this concept was operationalized as "2 miles from city hall" (Warner 1978). Land uses and socioeconomic groups were mixed in dense city centers; upper-income residents prioritized proximity to powerful institutions like government offices, banks, schools, and churches, and often lived in relatively close quarters with lower-income residents or recent immigrants (Jucha 1979)—as well as industrial activities and "nuisance" activities like polluting factories or dumping sites. Local rules regulating what sorts of uses could be built where (zoning) only began emerging nationwide in the 1920s, so they had little influence on land use when streetcar systems were rolled out.

In the mid-1800s, however, there was latent demand for what would become the prototypical American suburban lifestyle (Warner 1978). Notes Jucha (1979: 304):

> Romantic attitudes concerning nature flourished at this time… romanticism lay behind the encouragement of landscape gardening, which in turn spawned the city park movement and the romantic suburb… The urbanite who fled the city for the countryside wanted to evoke as rural a quality about his new home as the suburban situation would permit.

Though some of the wealthiest Americans had the means to construct estates at the edge of town and accessible only by horse and carriage, most urbanites had no ability to transport themselves routinely back and forth between the city center (where jobs were present) and the exurban edge. In this way, streetcar technology enabled urbanites to realize something closer to these rural, romantic aspirations by moving to less dense suburbs. But pastoral perspectives were not the only motivators for urban expansion. Others held an aversion to growing immigrant populations, such as the wave of Catholic immigrants who came to Boston after Ireland's potato famine of the 1840s (Warner 1978).

Moreover, streetcars enabled housing construction on less costly land further out. Streetcars transformed peri-urban areas into "streetcar suburbs," offering housing in less densely populated settings but within commuting distance of jobs. As we detail below, their efficiency and affordability led to increases in urban land area expansion, with less dense housing developed in patterns that closely tracked the linear extension of streetcar routes (Jucha 1979; Warner 1978; Xie and Levinson 2010).

A modest body of literature focuses on US streetcar suburbs. Most emphasize the history of streetcar development and the suburban development that followed in specific cities. Sam Bass Warner's 1978 seminal *Streetcar Suburbs* offers an authoritative take on the development of the streetcar and its land use impacts, with a focus on Boston. Detailed historical accounts also exist for Philadelphia; Hayward-Hobbie subdivisions in Rochester, New York; Shadyside in Pittsburgh; Brookland and Brightwood in Washington, D.C.; Minneapolis and St. Paul; Hillcrest in Little Rock; and Richmond, Virginia, among others (Glock 2009; Jucha 1979; Nichols and Smith n.d.; Prince 1979; Somerville 2018; Zie and Levinson 2010; Zylstra 2011). We pulled from those examples as we developed this case study; we considered studies of streetcar suburbs in the United Kingdom and other countries out of scope for this historical example.

Developers clustered new residential enclaves along streetcar lines, and real estate and streetcar lines were often developed in tandem. In other words, streetcar expansion did not just respond to increasing demand for transportation to a given area (by making it feasible to traverse the urban region more quickly), but also created demand for new housing, retail, commercial, and industrial development by making new areas accessible from central neighborhoods (Somerville 2018; Xie and Levinson 2010). Development often clustered tightly around streetcar lines, with density declining significantly outside of walking distance to the line, leading to "finger-shaped extensions" outward.

Xie and Levinson (2010) apply statistical methods to historical maps of streetcar lines and housing development in the Minneapolis–St. Paul urban area, finding that the residential density of a tract of land was significantly and positively correlated with five-year lagged streetcar line density. In other words, the extension of streetcar lines significantly increased the volume of land devoted to housing along those lines five year later (compared to areas without streetcar lines). In contrast, lagged residential density was *not* a predictor of streetcar line density, meaning that the lines did not necessarily follow pre-existing development. This corroborated their hypothesis that the deployment of streetcar lines, especially those extending into undeveloped suburban land during the electric streetcar era, brought new residents and new housing to the areas they reached.

Numerous historical accounts of other cities offer similar findings though through the use of qualitative descriptions or visual inspection of maps. Warner (1978) describes the impact of streetcars on land use in Boston using the language of classic urban economics. In his account, the introduction of the streetcar resulted in a class-differentiated living pattern—as opposed to the largely mixed-income neighborhoods that predated the technology. The wealthiest residents had multiple options for transportation and housing (since they could afford services other than just streetcars, like horses and buggies) and tended to live furthest into the countryside; streetcars did not heavily impact the location or size of upper-income housing. With streetcars, middle-income residents could live in the “ring” closer to the city, and had a consistent commute via streetcar to centrally located offices. By 1900, this ring stretched ten miles from Boston’s city hall, and its building stock consisted mostly of detached single-family houses. Lower-middle income residents, on the other hand, moved more frequently between different jobs or work locations, and thus lived closer to the city to have better access a variety of destinations. This ring extended three and a half miles from city hall and featured densely clustered housing such as attached rowhouses or multi-unit buildings. Each concentric ring of financial status had successively smaller lot sizes and homes than the ring outside it. The center now housed the poorest residents—often newly arrived immigrants—in high-density, low-quality apartments. This area also contained industrial facilities, spurred in part by the development of the railroad around the same time.

The preceding narrative focuses on a class-based residential distribution. Streetcars likely also impacted the spatial distribution of residents along racial lines, but we could not find any literature on this topic. In many cities, during certain time periods, people from minority communities were not allowed to ride streetcars (Zylstra 2011). Similarly, we could not find specific literature on how the impacts of streetcars were experienced along gender lines, such as making it more or less safe for women to travel or changing the areas where homemakers spent most of their time.

Development often clustered tightly around streetcar lines, with density declining outside of walking distance of stops, leading to linear, branching, “finger-shaped extensions,” as noted (Xie and Levinson 2010), though the density and housing forms within those extensions in many cities may have aligned with Warner’s description of concentric rings in Boston. In many urban areas, the spatial forms resulting from late-1800s streetcar development persist to this day, long after the streetcar lines themselves were dismantled (Lang, LeFurgy, and Nelson 2006).

Streetcar suburbs featured new forms of retail and commercial spaces. Storefronts elongated to become more visible to people viewing shops from fast-moving trolleys (Lang, LeFurgy, and Nelson 2006). Commercial districts assumed linear urban forms following streetcar lines, as opposed to the clustered forms they typically took in traditional pedestrian-focused commercial cores (Nichols and Smith n.d.). These “taxpayer strips” were the precursor to car-based strip malls that accompanied private automobile ownership by the mid-1950s (Lang, LeFurgy, and Nelson 2006). In addition, streetcars made it easier for people to travel to entertainment venues and other attractions outside of cities. This led to the development of new entertainment districts and amusement parks, which in turn contributed to the growth of the leisure and entertainment industries (Hilton and Due 1964).

The ownership structure of streetcar companies played a role in the way they expanded. Unlike today’s publicly owned highways and transit, streetcar systems were privately owned, often by real-estate investors or other prominent local businessmen (Xie and Levinson 2010). But city governments often required them to hold publicly issued franchises. The relationship of private streetcar companies with city governments varied. In the Minneapolis–St. Paul region, the streetcar company was regulated as a franchised monopoly, with two main conditions: a five-cent flat fare combined with the ability of local city councils to order the company to build any line deemed reasonably necessary (Xie and Levinson 2010). Some cities, including Chicago and Philadelphia, granted independent companies franchises for streetcar services on different corridors; these were eventually consolidated.

The real-estate interests of the streetcar companies' owners or investors were a driving factor in the pace and scale of streetcar line expansion and associated urban development. Businesspeople earned a profit from selling or developing land that increased in value due to line construction, and conversely could secure a ridership base for their streetcars by constructing housing along lines. Residents were mostly "captive" riders since most cities in the late 1800s and early 1900s had no other form of transportation accessible to working-class people. Xie and Levinson (2010) hypothesize that this incentive structure, and high profits in the late 1800s, led developers in the Twin Cities—and likely elsewhere—to overbuild the streetcar system. They constructed more tracks than would be economical to maintain and developments that were too sprawling to provide sufficient ridership for the streetcars and suburban businesses. This overbuilding, in turn, contributed to the eventual decline of the system.

The decline of streetcars in the US happened gradually starting in the 1920s (Slater 1997). There are multiple theories to explain this decline. Some argue that there was a conspiracy by auto manufacturers and suppliers to replace streetcar lines with their own vehicles; others point to the financial and technical superiority of internal-combustion-powered buses. Evidence on the accuracy of these theories is inconclusive (St. Clair 1981). Slater (1997) argues, for example, that buses had lower per-passenger costs stemming from smaller capital expenditures when compared to streetcars due to them not needing tracks nor being required to pave the streets where they operated. Yet, St Clair (1981) shows that streetcars were more profitable than buses on a per-passenger basis. Both streetcars and buses, however, were affected by the nationwide decline in public transit ridership that steadily continued throughout the 20th century, with a short respite during the second world war due to gasoline rationing and limited automobile production.[16] Transit ridership decline coincided with mass private automobile ownership, which encouraged increased sprawling living and working conditions, making public transit ineffective for most trips in all but a handful of denser urban locations.

How did streetcars impact outcomes in terms of racial and social equity?

Those who benefitted and lost out from the rollout of electric streetcar technology varied in terms of both income and race. Middle-income urban residents benefitted most from the vehicles, because they had adequate income to buy housing in areas made newly accessible and could afford to use them to commute. Upper-income residents already had access to a range of housing locations and transportation modes, so they benefitted relatively less. Lower-income residents (including newly arrived immigrants) often lacked the incomes needed to live in streetcar suburbs or use the vehicles for regular commuting.

In most cases, households increased transportation expenditures after they began using streetcars, because they had previously walked to most destinations. That increase in transportation costs, however, was not necessarily concerning from an equity perspective; there seems to have been ample latent demand for such affordable public transportation, especially among middle-income households who wanted more options to facilitate new living options (Warner 1978).

Streetcars became important sites to enforce or contest racial hierarchies, especially laws that segregated Black and White people. Zylstra (2011) details how Philadelphia's race hierarchies and segregation—and resistance against them—played out in the arena of streetcars; Bates (2016) explores similar dynamics in Tennessee under Jim Crow in the early 1900s; and Meier and Rudwick (1973) do so in the Virginia context. In some cases, the trolley companies themselves—and Black people—opposed streetcar segregation.

Management of some streetcar companies believed those laws were bad for business, since they deterred Black riders, were challenging to enforce, and exposed companies to legal liability for failing to enforce segregation. Conductors sometimes struggled to determine a rider's race in split-second judgements. Zylstra (2011) describes how some operators prioritized enforcing segregation over efficient streetcar operation, for example by stopping streetcars for long periods if Black passengers refused to disembark. Bates (2016) notes the tension between some White people's political positions and their cultural knowledge: They supported segregation conceptually and upheld the enforcement of discrete racial categories, but simultaneously acknowledged the spectrum of racial diversity encountered in daily life. Moreover, they were sometimes unwilling to sacrifice personal convenience (i.e., because of delays in streetcar operation) in the service of the political project of segregation.

Black leaders in Richmond, Virginia, in addition to responding to the injustice and humiliation of segregation, expressed deep concern that giving enforcement powers to streetcar operators ("hot headed and domineering young White men") would lead to increased violence (Meier and Rudwick 1973: 481). Zylstra (2011) adds that, in Philadelphia, streetcars were often operated by Irish immigrants, who were not necessarily considered White at that time, and who stood to benefit from cementing their status as White by enforcing segregation against Black people. Streetcar boycotts and protests in the early part of the 20th century were a predecessor to the bus boycotts that played a critical role in the civil rights movements in the 1950s.

While streetcars did not themselves cause segregation, Jim Crow laws, or other racist policies, their cultural and economic prominence made them key sites for social unrest, where stakeholders fought to cement or resist those policies for their benefit. This dynamic was not unique to the streetcar. Transit, as a public space and arena of major economic and symbolic importance continued—and likely will continue—to epitomize tensions relating to prevailing political and cultural systems.

How did streetcars impact other sorts of outcomes?

As we noted, streetcars did not directly improve most people's employment access, since they often had previously chosen housing locations to ensure the ability to get to work by walking. The main benefits of the technology, however, did include increased access to more affordable, larger, or higher-quality housing, plus access to the green space and the retail or commercial establishments that developed in streetcar suburbs. The indirect economic effects of streetcars led to job creation, including in the real estate, construction, leisure, entertainment, and to some extent industrial sectors, since manufacturing facilities sometimes located along new streetcar lines, as in Rochester (Somerville 2018).

The introduction of electric streetcars had a significant impact on the health of city residents because they were cleaner than the horse-drawn carriages preceding them. When streetcars were introduced, most city residents were exposed to air and water pollution and unsanitary living conditions. The electric streetcar limited pollution by eliminating the need for horses, which produced manure and urine, leading to unpleasant odors and unsanitary conditions. Granaries needed to maintain the thousands of horses inhabiting most cities also began to disappear, decreasing rodent problems that were linked to lice- and tick-borne diseases (Rosner 2010). Streetcars, moreover, had none of the tailpipe emissions associated with coal-powered steam engines used for railroads.

Electric streetcars also helped reduce congestion by being faster and more efficient than horse-drawn carriages. This helped reduce the amount of time people spent in movement, which in turn reduced their exposure to air pollution and other health hazards. Electric streetcars, moreover, promoted the development of new residential areas outside of the city center, which provided many middle- and upper-income residents with access to cleaner air and better living conditions. However, these benefits were not nearly large enough to offset the health challenges most cities faced due to overcrowding and infectious diseases, as well as industrial pollution and poor working conditions.

Impact of public policy on the rollout of streetcars and their land use impacts

The public role in the rollout of streetcar lines throughout the country was not nearly as direct as, say, the involvement of the federal government in the construction of the Interstate Highway System. Private investors built virtually all of the streetcar lines completed in the late 1800s and early 20th century, following their profit motives. Few received public subsidies to invest in their projects.

That said, local governments did often provide franchises to streetcar investors, as we noted. In some cases, these franchises directed where new lines would be built. They also restricted fares, in some cases making it difficult for private operators to maintain profitability (Bloom 2023). Given the widespread rollout of the technology, it appears that the franchise system did not prevent large-scale construction. But tight fares may have contributed to decreased transit ridership over the long-term, as services declined in quality and people shifted to increasingly affordable and convenient car use.

Local and state policies enabled streetcar investors to link line construction with development on the urban edge. By allowing investors to build on previously agricultural or natural land, regional economies grew—but doing so helped produce the class- and racially segregated dwelling patterns that followed streetcars. Streetcar development without such suburban development could have, in theory, encouraged denser, mixed-income neighborhoods in central areas, but that would have required public entities to block greenfield development, such as by using greenbelts or other growth controls.

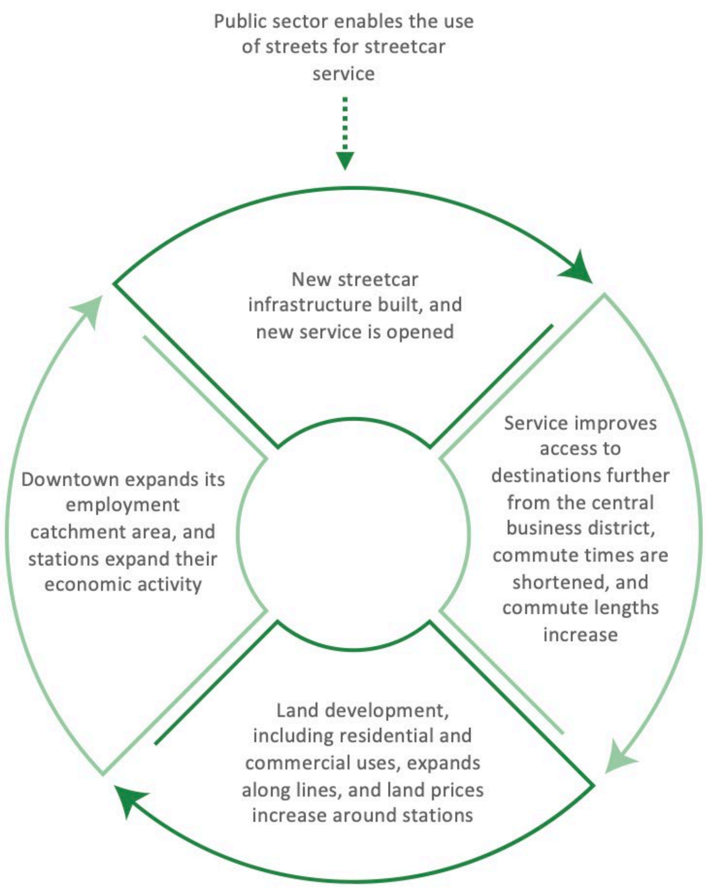
A select number of cities, including New Orleans, Philadelphia, and San Francisco, kept their streetcar systems operating in the postwar period and continue to offer service on them today. As a result, they became integrated into the mainline public transit systems of those cities. This has meant the long-term public subsidy of those lines. Because there have been so few streetcar lines kept open, it is not clear whether there was any specifically different outcome resulting from their use compared to that of bus lines in other cities, which also required public subsidies.

Over the past few decades, several US cities—including Atlanta, Cincinnati, Charlotte, Dallas, Detroit, Kansas City, Oklahoma City, Portland, Salt Lake City, Seattle, Tucson, and Washington—funded streetcar lines, in part through federal grants.[17] The construction of these new lines was typically premised on the hope that they would generate new economic development nearby. These public investments thus assumed similar outcomes as had occurred thanks to private investments a century before. Initial analysis suggests that they had varied impacts on economic development in terms of employment trends (Hinners, Nelson, and Buchert 2018).

The streetcar–land use feedback loop

In Figure B.1, we diagram the feedback loop connecting streetcars, accessibility, land use, and related activities. By its nature, this feedback loop does not necessarily have a starting point. Streetcar line construction, however, typically did necessitate government approval before the cycle commenced.

Figure B.1 Land Use Feedback Cycle for Streetcars



As governments approved the construction of streetcar lines and provided access to parts of the street, private companies, using their own capital, would build these lines. Lines allowed access to new origins and destinations, and allowed workers to have either faster or longer commutes. This enabled housing construction further from downtown, leading to more suburban residents, itself likely impacted by a latent demand for suburban living. Due to lower land prices, this housing was often more affordable than the comparable dwellings in the urban core. Furthermore, developers built commercial areas around the new infrastructure. Many of the residential and commercial developments built in the areas near streetcar lines were constructed on land owned by streetcar investors themselves.

This feedback loop was initiated in many US cities at the end of the 19th century. Its success encouraged developers to repeat the effort. As it became apparent that this link between streetcar technology and development was profitable, developers repeated the cycle, investing in new lines. These new lines, in turn, spurred more accessibility and created opportunities for new development.

What would an alternative universe look like?

A potential parallel universe would be one where the use of streetcars had not declined and had continued to be a dominant mode of transportation. One theory explaining the decline of streetcars is that, because the companies operating them were responsible for laying tracks and paving streets where they operated, their upfront costs were higher compared to other modes of transportation. Buses and cars benefited from public investments in roads, making their upfront costs much lower.

We imagine two hypothetical ways by which public policy could have evened the playing field. First, governments could have covered part of the cost of streetcar operations using public funds. This would have encouraged more streetcar line development, and potentially made it possible to continue laying tracks. Policymakers who combined such a policy with allowances for fare increases over time could have, in addition, made it feasible for streetcar operators to improve their vehicles and continue attracting riders. Second, governments could have directly charged *other* roadway users—particularly car drivers—for the use of the roadway. This could have required the implementation of road user charges or higher fees on the purchase of new automobiles. In either case, this would have made it more difficult for people to switch out of streetcars into private cars.

Another possible alternative universe is one in which streetcars had not been introduced. Given the evidence that streetcar lines encouraged rapid construction on the sprawling periphery of urban areas, no streetcars would have likely meant much higher concentration of economic and residential development in the walkable, central parts of US urban areas. US cities may have become more densely populated during the period before the advent of the automobile.

Implications for the AV ecosystem

Drawing a parallel between the history of streetcars and a potential AV future, a lesson is on public-sector support for a technology. In this case, we showed how indirect public subsidies for buses and private cars, in the form of investment in roadways and other automobile infrastructure, were one potential explanation for the demise of the streetcar. Likewise, the extent to which AVs benefit from indirect (or even direct) subsidies from the public sector could determine the scale they reach in the future, and what form their eventual deployment takes. Conversely, if the cost of making and using AVs reflected the externalities they cause, including the infrastructure they operate on, it seems unlikely that they would be able to compete against other technologies that might receive public subsidies.

Additionally, different jurisdictions will likely regulate AVs differently. As with streetcars, different regions may put more or less restrictive operational requirements on AV companies making it easier or harder for companies to turn a profit. In fact, this has already started happening in multiple states that have different restrictions and requirements for AV testing in their jurisdictions. In the future, this could lead to cities and states that are otherwise similar having different AV futures, such as different AV modal shares or different extents of change on the built environment to accommodate AVs.

Like streetcars, AVs could expand the footprint of urban metro areas by reducing the time and potentially cost of transportation, making it easier to commute from further away from the central business district. This, in turn, could lead to increased land development in suburban or rural areas, and potentially increase the cost of this land.

Another potential parallel between streetcars and AVs is the scale at which they influence land-use patterns. As described, predecessors of electric streetcars, such horse-drawn omnibuses and steam-powered cable cars, were similar to electric streetcars, but had little influence on land-use patterns because their cost or functional limitations prevented most people from using them regularly. Similarly, AVs may be on the road in the not-too-distant future, but unless they are affordable to a significant share of the population and can operate well in urban centers with many traffic irregularities and types of modes, they are unlikely to reach the scale needed to meaningfully influence on urban land use.

Highway infrastructure

Controlled-access highways, or networks of interconnected, multi-lane roads designed for high-speed travel, changed the landscape of US cities, suburbs, and rural areas. Highways made car travel cheaper and easier, while contributing to suburbanization. They encouraged a shift of the freight transportation system from railways and canals onto trucks. They also spurred economic growth in areas near roads, while contributing to economic decline in sections of inner cities adjacent to highways and in small towns far away from them. Combined with racist housing market policies that supported single-family homeownership for White Americans, highways contributed to racial inequity by intentionally and disproportionately displacing communities of color during their construction and then by segregating communities of color from opportunity. AVs could have similar impacts on our society if policies are not intentionally designed, not only in the transportation realm, but also in the land-use and housing realms.

What are highways?

A highway, defined broadly, is "any public street, public alley, or public road, including a privately financed, constructed, or maintained road that is regularly and openly traveled by the general public."[18] The history of highways (in its broader definition) can be traced to ancient civilizations, such as the Romans who built stone-paved roads for military purposes (Schwartz 2015). For the purpose of this case study, however, we refer highways as controlled-access roadways, which designed for high-speed vehicular traffic, with traffic flow—ingress and egress—regulated, and non-motorized vehicles forbidden. Controlled-access highways cohere into a network of interconnected, multi-lane roads designed for high-speed travel between destinations by wheeled, motorized vehicles. Highways are constructed with a hard, smooth surface, such as concrete or asphalt, and feature high traffic volumes. The paradigmatic US highway network is the Interstate highway system.

The concept of roadways designed for high-speed movement is a relatively modern phenomenon (Norton 2011). In the United States, a surge in the use of bicycles in the late 19th century resulted in increased public pressure for better roads, which at that point were mostly dirt. The bicycle industry and bicycle advocacy groups promoted highway construction through the Good Roads Campaign to improve investments. In 1895, the first "object-lesson" roads—those built to convince voters of the convenience and value of building better roads with up-to-date techniques—were completed in Atlanta, Georgia. This new technology provided a smooth and water-resistant roadway, built with layers of macadam, sand, and earth.[19]

The invention of automobiles and their fast-paced growth among US households encouraged the public and their representatives to push for roads better conditioned to a high volume of fast-moving cars. The Good Roads campaign was engaged by automobile enthusiasts and persuaded federal and state governments to invest in road construction and improvement, also motivated by the interest in improving rural roads; New Jersey became the first state to provide funding for roadway improvements, with all states doing so by 1928 (Schwartz 2018). The fact that Americans were rapidly purchasing automobiles expanded political and economic support for them (Schwartz 2015). This momentum led to the creation of the Federal-Aid Road Act of 1916, which appropriated $75 million ($2.2 billion in 2023 dollars) over five years to be apportioned to the states by formula to develop hard-surfaced roads. The law, which focused on rural communities with the goal of connecting farmers to markets, mandated the creation of state highway agencies to receive this federal aid. Until this law, most roads in the United States were constructed either by localities or by private investors, many relying on tolls to fund their costs; this road act transformed that notion and definitively ensconced the federal government and its state partners into road construction (Weingroff 1996a).

In 1944, President Franklin D. Roosevelt authorized a National System of Interstate Highways, meant to be a network of limited-access roadways crisscrossing the country, but did not provide funds for its construction. In 1956, motivated by the critical role that roadways played in the advance of the US Army in Europe during World War II, President Dwight D. Eisenhower signed the Federal-Aid Highway Act of 1956, establishing a financing system to pay for this network. The law created the Highway Trust Fund, producing a continuous stream of revenue from highway user fees, primarily gas taxes (Weingroff 1996b). Over the next few decades, the federal government funded states to build thousands of miles of highways, connecting cities, towns, and rural areas across the nation.

The development of a national highway system had a significant impact on the United States' ability to move people and goods more quickly, more directly, and more cost-effectively. This, in turn, helped to lower the costs of goods and services and improve economic efficiency. Highways also made it easier for people to travel long distances, whether for work or leisure, helping to stimulate economic growth in different regions of the country (Shatz et al. 2011). But their construction also had negative consequences: increased car emissions and greenhouse gas pollution, destruction of ecologically sensitive land and urban neighborhoods, and promotion of more sprawling development patterns. The federal government also funded highway construction but not investments in alternatives, like improved intercity railways, urban public transportation, bikeways, or pedestrian improvements. This embedded the automobile as the key transportation mode for most trips in the United States.

Land use impacts of highway infrastructure

Direct impacts: Demand for land in suburban and rural areas near highways

Highway construction created opportunities for people and goods to move more easily between cities and towns, encouraging changes in where people lived and worked. The increased efficiency and lower transportation costs to and from remote areas using highways caused land near those roads to become more attractive to residents, business, and manufacturing firms, which, in turn, caused this land to be converted into these uses and become more populated (Sanchez 2004), often outside of central cities. This encouraged the development of multipolar urban regions, creating edge cities with their own agglomeration effects. This, in turn, made the use of transit more difficult. Most localities and state governments mounted few roadblocks to this development, allowing construction on formerly natural or agricultural land. This development pattern is less common in some other developed countries that—even in the context of highways—prioritized infill development and protected unbuilt land through growth boundary policies. Examples include the United Kingdom's Green Belt (Rankle and Barton 2023) and France's *zero artificialization* policy (Ministry of Ecology 2019).

Highway development destroyed many inner-city neighborhoods, since political officials chose to route roads in such a way that houses, businesses, and churches were raised to make room. According to estimates from the U.S. Department of Transportation, more than 475,000 households and more than a million people were displaced nationwide because of federal roadway construction. As discussed in detail in the section on social equity below, this neighborhood destruction was often targeted at communities of color as part of an intentional effort at urban renewal to remove blight.[20]

Highways were accompanied with other forms of infrastructure, like bridges and connectors, which are roads linking one roadway to another. The area required for the construction of connectors, such as cloverleaf interchanges, spans beyond the linear surface required for highway lanes, thus necessitating a higher level of land utilization. Since highways increased the amount of car travel, they also spurred demand for parking space; local zoning policies in most parts of the United States, meanwhile, further encouraged this demand by mandating parking requirements for developers building new projects.

Secondary impacts: Suburbanization, population loss in central cities, and loss of agricultural and natural land

Highways allowed people to travel longer distances quickly and affordably, making it possible to live further from urban centers while still being able to commute to work downtown. This had ramifications on where people lived. A new highway passing through a central city was associated with an 18 percent decline in its population on average (Baum-Snow 2007)—a product of highway construction itself (which displaced people) and the suburbanization it supercharged. Had the Interstate highway system not been built, Baum-Snow (2007) estimates, national central-city population would have grown by about 8 percent, rather than declining by 17 percent between 1950 and 1990.

Suburbanization provoked by highway construction must be contextualized with other simultaneous efforts. The Federal Housing Administration's (FHA) mortgage insurance program made it easier for middle-income families to purchase homes in the suburbs, contributing to the process of suburbanization. The FHA's program incentivized builders to construct homes outside of urban areas, as the agency's minimum standards often required more space to build than was available in urban areas. The GI Bill, passed in 1944, also encouraged suburbanized homeownership by providing low-cost home loans with no down payments for World War II veterans. And, beginning with the Housing Act of 1949, the federal government began funding urban renewal programs that supported the demolition of housing and businesses in center-city communities, which undermined neighborhood stability and further encouraged suburbanization (Wilson 1966).

In parallel with the rise of the automobile, moreover, many localities developed land-use regulations favoring the creation of low-density communities largely constituted of detached, single-family housing—rather than the mix of single homes, small-scale apartment buildings, and larger structures that predominated during the streetcar suburb era. Localities established minimum lot size and square footage requirements for new homes, making it difficult to build other types of more affordable housing.[21] Many cities also explicitly prevented the construction of subsidized housing, even in central neighborhoods where public transportation options were most effective (Parson 2005).

Demand to ride passenger trains was also affected by the introduction of highways—and the lack of simultaneous public investment in railways, which were then mostly operated privately. Highways displaced trains as the most convenient mode of transportation, to the point that by the 1970s, most private rail networks had gone bankrupt (Thompson 1994; Trancik 1986). Fewer available passenger rail services encouraged automobile use, thus spurring more monofunctional sprawl rather than the dense, mixed-use neighborhoods that accompanied railroad stations built during previous periods.

In addition to influencing residential location, the highway system altered *firms'* locations by increasing the attractiveness of urban fringe land relative to city land. First, highways reduced firms' dependence on rail and water transportation systems, enabling firms to move away from established centers. Second, highways enabled firms to more easily access markets located in other cities, which potentially increased firms' profitability when they located on routes between cities. The construction of Interstate highways in rural counties increased economic activity in counties they pass through (Chandra and Thompson 2000; Michaels 2008), but they simultaneously drew economic activity away from nearby counties that did not contain Interstates (Chandra and Thompson 2000).

This suburbanization of jobs was also aided by the invention and expansion of containerization, which suburbanized the logistics industry and contributed to sprawl (discussed in the following historical example). Developers constructed commercial areas, such as strip shopping centers and enclosed malls, along highways. Localities reinforced their land-use ordinances requiring minimum parking to accommodate consumers increasingly reliant on automobiles; in so doing, localities further encouraged this reliance. This urban structure in which services, groceries, and other daily needs were clustered in places beyond walking distance from most residential communities further led to cars becoming the default mode of transportation for suburbanites (Fishman 1990).[22] This in part explains how residents of the United States drive twice as much on average as people in France, Germany, or the United Kingdom. Those countries also have highway networks, but roadway construction there caused less destruction of central-city neighborhoods and those countries provided fewer incentives for residents to buy homes on greenfield land.[23]

As highways lowered transportation costs and opened tracts of land for development, agricultural and natural land was converted for other uses. Each additional mile of Interstate mileage reduced agricultural land by 468 acres on average (Mothorpe, Hanson, and Schnier 2013). Vegetable production was the only agricultural subsector to benefit from suburbanization, while the livestock sector was most adversely affected (Lopez, Adelaja, Andrews 1988). Highways also reduced biodiversity, mainly because they fragmented habitats, exposed them to human impacts, and because of direct mortality (e.g., animals being hit by cars) (Gonzalez-Gallina et al. 2016).

The loss of agricultural land had negative environmental consequences, including in terms of stormwater management, recharging of aquifers, open space preservation, and air purification (Lavingo et al. 2004). Agricultural land converted into suburban development, or urban sprawl, carries negative externalities including urban decay, air and water pollution, and inequality (Nechyba and Walsh 2004).

Highways and social equity

The US highway system has had differentiated impacts on various groups of people. As noted, in the 1950s and 1960s, local and state governments routed highways through neighborhoods whose residents were predominantly people of color and people with low incomes, resulting in displacement and the disruption of social networks. Construction led to the physical destruction of homes and businesses, and also the erasure of cultural landmarks and important community spaces. Moreover, highways often acted as barriers between neighborhoods, isolating already marginalized communities (Archer 2020; Karas 2015; Reft, Phillips de Lucas, and Retzlaff 2023). They have also disproportionately exposed pedestrians and bikers of color and those with low incomes to traffic violence (i.e., fatalities and injuries from traffic incidents) (Raifman and Choma 2022).

Suburban development was particularly beneficial for middle-income and affluent White Americans, who chose to move to suburban areas with well-funded schools and amenities. This process is commonly known as "White Flight," and it occurred particularly after the influx of Black migrants from the rural South to cities in the North and West as part of the Second Great Migration that began during World War II (Boustan 2007). Due in large part to the racist US housing market that was codified through redlining, racial covenants, GI Bill home loans, private lending practices, and zoning regulations, many Americans with low incomes and people of color remained in neighborhoods with few economic opportunities and limited access to effective transportation (Fernandez et al 2023; Rothstein 2018).

The phenomena described above created a pattern of suburbanized employment—but low-income workers and workers of color living in central cities (Ellwood 1986; Holzer 1991; Kain 1968; Wilson 1987). Known as spatial mismatch, this pattern contributes to higher unemployment rates and longer spells of joblessness among lower-paid workers (Andersson, Klaesson, and Larsson 2014; Brueckner and Zenou 2003). According to one estimate, shorter commute times are a significant predictor of upward economic mobility (Chetty et al. 2014), and we know from evidence that the employment opportunities of Black people, women, and older workers are more sensitive to the distance between residences and job location than other subpopulations (Andersson et al. 2018). These factors combined explain how job suburbanization disproportionately affected Black employment rates (Miller 2018).

The reduction of manufacturing employment, decades of urban population decline, and suburban growth have led to disinvestment in cities and concentration of higher-income residents in suburbs (Mallach 2012). Some cities have harnessed assets to promote new economic opportunities (e.g., Pittsburgh's shift from being a manufacturing to standing out as a health and technology hub[24]), but the uneven distribution of resident socioeconomic characteristics, declining property values, and degraded physical environments in many urban cores still impede revitalization in many places (Mallach and Brachman 2013). As a result, central cities—which often bear the burden of funding transit and affordable housing—lack the tax base to support a robust and equitable transportation infrastructure.

Competition for limited resources in legacy cities facing long-term declines in population and economic wellbeing constrained planners' ability to pursue additional transportation options, such as improved bus and rail services (Ganning 2014). This constraint compounded as decreasing population density limited the efficiency of public transportation (Schwanen and Mokhtarian 2005). Legacy cities now face difficult decisions that pit concerns about gentrification and displacement against efforts to improve transportation access for households with low incomes (Tighe and Ganning 2015).

Highways and the environment

Highways contribute to air, water, and noise pollution, as well as the destruction of natural habitats. As highways have been built and expanded, people have driven more; US vehicle trip mileage increased from 302 billion in 1940 (2,286 miles per person)[25] to 3.26 trillion in 2022 (9,637 miles per person).[26] This increase has spurred the emission of particulate pollutants, and now transportation is the US's largest source of greenhouse gas emissions, the leading cause of climate change. Climate change is likely to disproportionately affect people with low incomes and people of color through extreme weather, environmental degradation, and labor market dislocations (Patnaik et al. 2020).

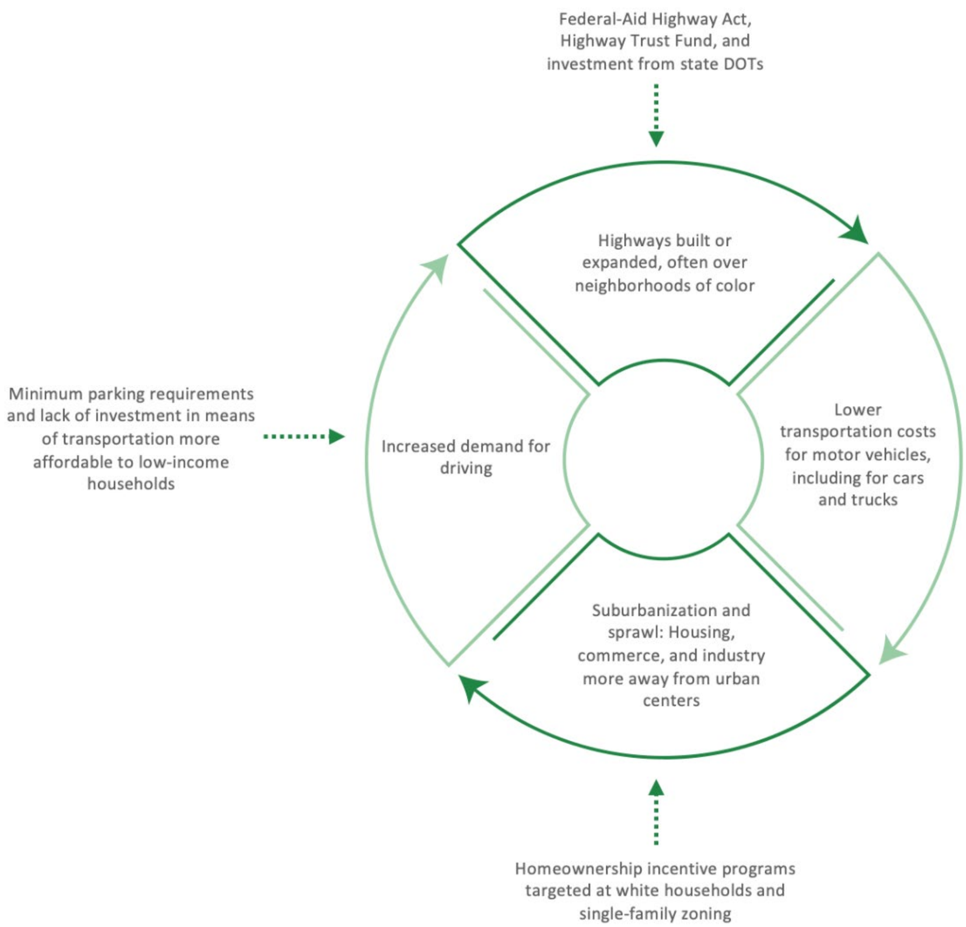
Passenger vehicles and trucks are a source of other air pollutants, including carbon monoxide, nitrogen oxides, particulate matter, and sulfur dioxide (EPA 2017). These pollutants can damage immune systems and cause respiratory and other health problems. People living, working, and learning within 150 to 300 meters of highways are disproportionately subject to dirty air and loud ambient noise (Samuels and Freemark 2022). This, in turn, causes health problems, including lung disease, stroke, and premature birth. Roadways also tend to reduce the property values of nearby residences.

Environmental impacts disproportionately affect low-income communities and communities of color, which are more likely to be located near highways and other pollution sources (Samuels and Freemark 2022). Non-Hispanic Whites experience 17 percent less air pollution than they create through driving, yet Black and Hispanic people experience 56 percent and 63 percent more, respectively (Tessum et al. 2019). This disparity can be partly explained because communities of color and people born outside the US live closer to highways and industrial facilities on average (Boehmer et al. 2013).

The highway–land use feedback loop

Not only have highways affected land use, but land use has in turn affected the degree to which people use highways (Figure B.2). The introduction and expansion of highways led to an increased movement of people and jobs into the suburbs, away from urban centers. Due to policies like single-family zoning and minimum parking requirements, housing, commerce, and employment sprawled. The combination of sprawl and the abundance of dedicated car infrastructure turned car ownership and use not only into a convenience but an essential element of everyday living (Mattioli et al. 2020; Wang et al. 2018). This loop applies both to the original construction of highways and also to the continued use of highway infrastructure today.

Figure B.2 The Highway–Land-Use Feedback Loop



Notes: DOTs = Departments of Transportation.

State and federal departments of transportation invested in more highways (National Academies 2005) to alleviate congestion caused by induced demand (Hymel 2019; Hymel, Small, and Van Denver 2010). Induced demand is often ignored in the planning process since travel demand models do not typically include the feedback loops necessary to predict the induced travel effect (Volker, Lee, and Handy 2020). This cycle continues through investments in highway expansion with the purpose of reducing congestion, but the induced demand caused by the expansion often has the opposite effect.[27]

What would an alternative universe look like?

If highways had not been built at the current scale, the United States would likely have had less economic growth in its suburbs and perhaps nationwide, due to the logistics cost savings it unlocked for the country's industrial development (Smith 1994). However, the country may also have denser, more walkable cities and less suburban sprawl, and maybe greater racial equity.

If local and state leaders had not targeted highway construction at communities of color to intentionally demolish or disrupt them, many neighborhoods, like Overtown in Miami or Rondo in St. Paul,[28] would be more likely to be thriving today. Communities separated by highways may have evolved differently as their residents may have grown up in environments less segregated by these physical barriers. It is hard to separate the effects of highways, racialized zoning laws, and supports for homeownership that disproportionately benefited White Americans, but in the absence of all, the nation would likely have had more equitable, less segregated communities.

With fewer highways, the United States would also likely have less car usage and less pollution. This would increase public health through fewer immune and respiratory illnesses. Climate change may also have been lessened, and we might be facing fewer natural disasters. Fewer cars on the streets would have also meant different building and street design requirements that do not put so much emphasis on parking. Communities may also have invested more in transit and walkability in the absence of highways, but that is also uncertain. Demand for these services would have been higher since parking and driving is more difficult in central cities than it is in the suburbs. The nation may also have generated the political support to invest in a high-speed rail system—though it could also have encouraged more investment in aviation, which may have been worse for environmental outcomes than cars have been.

The effects of a lack of highways on housing are less clear, since not building them may have meant less land for housing. It may, in contrast, have meant that US cities would have developed more densely to accommodate more housing—but that would rely heavily upon alternative land-use policies.

Implications for the AV ecosystem

Highways reduced transportation costs, which encouraged people to drive more and move further from city centers. AVs may produce similar effects, not so much by making transportation cheaper, but by making travel easier (and potentially safer—though that has yet to be demonstrated). Rather than stressfully having to navigate traffic, an AV passenger will be able to do other things like sleep or work. This could, in turn, increase demand for longer travel and encourage people to move further from jobs.

Another key lesson drawn from this case study is how much parallel policies in the housing and land-use sectors affected the way that highways impacted the economy, equity, and climate. Similarly, parallel policies and programs should be considered when rolling out AVs, such as how exclusionary zoning regulations may affect how AVs in turn affect equity and access.

Container-based freight transportation

Containers are standardized freight boxes, made of metal and mostly 40 feet long, that are used to transport goods on ships, trains, and trucks. Container shipping has radically transformed freight transportation by reducing costs, increasing the ability to monitor movement, and enabling intermodal freight—transporting goods on multiple modes. We argue in this section that containerization had several primary associations with land use. The technology's direct effect was altering port locations; this required the construction of massive container terminals surrounded by acres of flat land to handle large ships and their goods, while freeing up land along waterfronts for redevelopment. The secondary effect of containerization—combined with advances in supply chain and logistics technology—was the development of suburbanized distribution centers and warehouses designed around truck access. A tertiary effect was the creation of truck-oriented big box stores.

Economic activity around the world has been altered in part because of the globalization of production and shipping, with containerization at its core (Hesse 2008). Its preeminence in global freight movement is part and parcel of the increasing flows of global trade. The ease of transport it provides, in turn, has reinforced globalization. If there is one technology that has come to define today's era of worldwide interdependence, it is the freight container.

Defining the technology

Until the 1950s, freight movement by ship, railway, and truck were disconnected. Ships carrying freight loads would arrive in city centers, where goods were unloaded, often to factories and warehouses directly adjacent to docks. Similar conditions were in place for railway lines. And trucks had little market share, to a large degree because of the inability to move large quantities of goods by a technology that was then still in development (the pallet and forklift were only invented in the 1930s). The development in 1956 of containers altered this equation, making it possible to move goods far more easily and enabling intermodal transportation. Rodrigue and Slack (2020) provide a detailed overview of the role of containerization in the overall freight system. We largely derive the following details from that text.

Industrial shipping firms developed the standardized container in 1965 and rapidly adopted it as the primary conveyance tool for global goods movement. It was initially a 20-foot-long box that was eight feet wide and eight and a half feet tall; this is referred to as a "twenty-foot equivalent unit" (TEU). TEUs are now the standard measurement for shipping; for example, the largest containership now in use has a capacity of 24,346 TEU.[29] This container evolved over the next few decades, expanding in length to a "forty-foot equivalent unit" (FEU), which is now the most common container used (the largest containerships thus can carry more than 12,000 FEUs). Containers average 22 tons of cargo and can be enclosed; with an open top; flat (for extra-sized goods); refrigerated; or designed for liquids.

The development of the standardized container followed a decade of advances in freight movement toward transporting goods using multiple modes. In 1952, shippers began using trailer on flat car services, placing truck trailers on rail cars directly. In the late 1950s, ports began installing gantry cranes and straddle carriers that removed containers from—and added containers to—ships. And in 1962, the Port Authority of New York and New Jersey opened the first port in the world specifically designed for container ships, the Elizabeth Marine Terminal, adjacent to Newark International Airport. Container terminals are considerably more efficient than the pier-based docks that preceded them because they eliminate onboard cranes and allow faster container removal from ships.

Since the 1960s, containerization became the name of the game in freight; the result was the widespread development of intermodal shipping. Goods could be transferred easily off ships and onto trains or trucks. Containerization both facilitated globalization and responded to globalization—meaning, it made it more feasible to move goods and its development advanced the shifting winds of commerce such that production facilities moved into different parts of the world. Rodrigue and Slack (2020) describe four "paradigm shifts" enabled by containerization, which we paraphrase here:

- The containerization of maritime freight, made possible by container-ready ships (referred to as cellular vessels, beginning in 1968) and ports. Some inland trucking services were introduced through container on flat car services in 1967, but these were largely point-to-point.

- The containerization of inland transportation systems. This meant it became increasingly common to move goods from ships onto trucks and trains. *Doublestacking* was introduced on rail services beginning in 1985 (meaning containers could be stacked one on top of another, increasing the effectiveness of freight rail services), and *reachstackers* and rubber-tired gantries made it feasible to transport containers at small- and medium-sized ports.

- The development of transmodal and intermodal freight transportation options. Transmodal options meant containers could be shipped across multiple freight modes using a set of contracts (tickets); intermodal options meant that a single contract could be used across multiple modes. The creation of automated terminals (beginning in 1995) and inland (meaning, non-seaport) container depots plus satellite facilitated this movement.

- Finally, integrated global shipping has become the norm over the past two decades. This has been made possible through the creation of electronic *bills of lading* (documents accompanying freight) and advanced container tracking made feasible through RFID and sensor technologies.

The process by which freight moves thus shifted. Goods are placed into containers, then transferred as part of the "first mile" to a terminal. They are then assembled through *composition* onto a conveyance, like a ship or a train. They move to an *interchange* point, where they might be transferred to another mode of transportation, at which point they move closer to their destinations. At the final terminal, the containers are *decomposed* (unpacked), with the containers or the contents of those containers delivered to their customers, as part of the "last mile" of shipping.

These steps are mediated through logistics, the process by which goods are transformed and distributed. The freight logistics process has not only required the establishment of a chain of intermodal transport between goods' origin and destinations, but also a number of additional facilities. Warehouses are used to store goods over a long period of time. Distribution centers consolidate, interchange, and decompose goods, often as part of the containerized shipping process. In some cases, these facilities are integrated into logistics zones incorporating a wide number of users simultaneously and allowing for synergies between freight arriving from, and departing to, different destinations. Each of these facilities operates within freight management systems operated by one or more companies that attempt to limit the storage of excess inventory and to achieve what some refer to as the "space/time convergence," meaning that goods can move as quickly as possible through space.

Land use impacts of containerization

In this section, we show how containers impacts land use—and how different land uses impacted the role out of containerization. Containerized transport freed up space in urban centers for redevelopment as it suburbanized the logistics industry and contributed to increasing sprawl. It has also encouraged the creation of new types of retailing that reduced the importance of small stores in the economy, first through big-box stores and later through e-commerce.

The location and design of ports, warehouses, distribution facilities, and transport infrastructure connecting them influence (and are influenced by) the development of the built environment. Hesse (2008) describes how the built environment has transformed over time in a series of urban form eras due to such technological changes (illustrated in Table B.2). Urban centers dominated human trade for most of recorded history; they encouraged goods storage and the sale at marketplaces, since they were able to connect products with people directly. The creation of maritime trade shifted urban growth to areas along waterfronts, leveraging shipping's reduced costs. In combination with industrialization, economic concentration has declined, first with the introduction of freight rail service—and more recently with containerization and intermodal shipping.

Table B.2 Transformation of Freight-Dominated Urban Forms Over Time

Urban Form Era	Function	Location	Examples
1. The city as a market place	Traditional place of goods exchange. (The city as a location for regional distribution)	Historical urban centres; temporary use of areas for warehousing and transshipment	Market places, traditional locations for urban retail, warehouses

Urban Form Era	Function	Location	Examples
2. Port cities, inland-port cities	Traditional place of goods exchange. (The city as a location for long-distance distribution)	Traditionally at shorelines, large inland waterways, intersections of distant trade-routes	Ports and port-infrastructures, storage buildings, warehouses, magazines
3. Rail freight terminals	Development of new transshipment points according to the industrial urbanization	Main stations and their backyards (close to the urban core, e.g., in "zones of transition")	Rail terminals and railyards, until recently in all major cities with railway access
4. Wholesale, freight forwarding	Suburbanization of distribution functions out of the core city (first outward drift)	Urban peripheric locations, close to highway interchanges	Transportation intensive land uses (commercial, industrial areas)

Source: Hesse 2008 (14: Table 1.1).

Direct impacts: altered port locations

The development of containerized shipping required creating port infrastructure capable of handling enormous container ships and unloading containers from ships with large gantry cranes. These ports have been increasingly connected to domestic supply chains through rail and trucking. These requirements meant that the docking areas for ships using previous technologies (i.e., no containers) no longer functioned well, and, in many cases, needed replacement. These transformations, which occurred beginning in the 1950s, had immediate land-use implications on the neighborhoods where freight ships used to dock and on the areas where they now do.

The modern, containerized supply chain produced "remainders," as Hesse (2008) calls them, where piers once connected to warehousing districts and, in some cases, factories. The center of many cities, like New York, were once marked by their connections to the shipping trade, as evidenced by the dozens of piers jutting out from the edge of lower Manhattan along the East and Hudson Rivers, through the 1950s (Figure B.3). These piers serviced not only the nation's preeminent office business district, but also an active garment district, warehouses, and other sorts of industrial activities.

Figure B.3 Manhattan's Waterfront, 1951

Source: NYC Map Tiles, City of New York, Licensed for Reuse Under Creative Commons CC BY 4.0. https://maps.nyc.gov/tiles/

The creation of a new containerized port in New Jersey in 1962, however, altered the land-use patterns in lower Manhattan. Buildings in the neighborhoods adjacent to the ports were vacated by businesses that had once relied on waterfront trade. A district once focused on industrial and working-class employment had to change. These transformations had several impacts on the built form of these "remainders." Neighborhoods once filled with working-class jobs transformed into places for the modern economy, for consumption, and for residential use (Cidell 2010). Former warehouses were converted into lofts and art galleries. Areas previously occupied by piers were rebuilt into office districts (Figure B.4). Other piers were dismantled or converted for other uses, such as retail shops or parks. Neighborhoods once central to the economy became filled with homes, many of them expensive.

Figure B.4 Manhattan's Waterfront, 2018

Source: NYC Map Tiles, City of New York, Licensed for Reuse Under Creative Commons CC BY 4.0. https://maps.nyc.gov/tiles/

The long-term impacts of this transition are multiple. First, transportation and industrial employment decentralized (the issue to which we turn in the next section). This reduced accessibility to certain types of blue-collar jobs for people living in the densest urban centers, though people may have gained accessibility to other types of jobs (such as white-collar employment) due to the redevelopment of former port zones. This loss of access to jobs in central, transit-accessible areas may have contributed to increasing car dependence for many who needed to travel to industrial jobs located further out and reducing access for people with lower incomes, who were more frequently people of color.

Second, the former port neighborhoods became, in many cases, more desirable for residents. These waterside neighborhoods featured good views and less of the industrial pollution that accompanied old ports. Portside locations in many US cities lost industry but attracted reinvestment from college-educated, wealthier residents; this phenomenon occurred not only in New York City, but also in places like Baltimore's Inner Harbor, San Francisco's Marina, Philadelphia's Old City, and South Boston (though the long-term viability of these transformations has varied; Baltimore's experience suggests that cities cannot always attract people to these locations). These outcomes may have played an important role in shoring up the economies of their respective cities.

Even as former port neighborhoods were transformed, the creation of new containerized ports had land-use impacts on the surrounding areas, too. The largest ports required vastly more surrounding flat land than the piers they replaced, notably for storing containers as they are transferred between ships and trains or trucks. The land use of these ports is a distinct, paved, and flat zone: Acre after acre of asphalt with stacked containers. Container ports are isolated from the surrounding urban or natural environment, neither allowing a mix of human uses (not that people would necessarily want to live nearby given high levels of air and noise pollution) nor providing for fauna or floral life.

In many cases, container port zones have access to land-based transportation infrastructure necessary to serve the trains and trucks that allow intermodal freight. Ports are often adjacent to highways and railroad trestles. In some cases, ports are surrounded by warehouses and logistics services. The adjoining ports of Los Angeles and Long Beach, collectively the largest in the country, are surrounded by huge logistics zones heading north along the Alameda Corridor made up of single-story warehouses and distribution facilities. These land uses thrive off direct access to the port.

Secondary impacts: Creation of suburbanized distribution and warehouses

Most of the growth in logistics and its associated land uses generated by containerization, however, has *not* occurred in the areas directly adjacent to ports. Because of the need to organize shipments between when they arrive from a transoceanic voyage and when they arrive at their final buyer, containers pass through distribution facilities inland along their trips (figure B.3). These distribution facilities are typically located near large metropolitan areas to serve their respective economies.

Though railways take on a large share of intermodal shipping, rail is generally less economical than trucking for trips of less than 500 kilometers (Rodrigue and Slack 2020). The ease of trucking—made feasible by the simultaneous implementation of highways—had major impacts on regional economies. Notes Hesse (2008: 15), "the motor truck forced the drift of economic activity away from the fixed topography determined by the location of cities and the layout of railway lines." Trucking allowed the national freight system to decentralize from historic ports and into the hinterlands of many urban areas, enabling more complex logistics and freight flows that linked everyone into globalization.

The container-based shipping system promoted using suburban or exurban locations for warehouses and distribution facilities. These locations have several major advantages (Rodrigue and Slack 2020). Because they have cheap and plentiful land availability, they can offer parking for trucks. They allow logistics enterprises to spread out over large facilities, enabling faster throughput and sometimes cross docking for goods moving from one truck to another. Sites are easily connected with the national highway network. The freedom of freight companies to locate in areas far from existing urban development has the added advantage of minimizing annoyance for neighbors, allowing round-the-clock cargo operation and thus further economic efficiency (Staley 1983).

The freight logistics system is built for fast services. Writes Bowen (2008: 380), "Strategically positioned warehouses are places at which far-flung production networks can be drawn together… from well-placed warehouses, deliveries can be made with a speed and frequency commensurate with demand-pull logistics." For this system to work, the modern freight enterprise is often connected to airports, along highways, and relatively close to metropolitan areas—but usually not located within them, at least within the most densely developed areas.

Distribution centers and warehouses, then, are a new form of land use arrayed along highways. These facilities are often located in logistics zones, so acres of land is composed of single-story facilities, surrounded by parking lots, themselves surrounded by encircling, truck-friendly roads. The container inspired a specific form of building—one-story structures with ports for trucks to approach and unload. This type of land use, as with the modern port, is largely monofunctional, being rarely within walking distance of residences or retail. It is inaccessible by anything other than cars.

This freight land use has had impacts on urban growth patterns and associated environmental effects. Researchers show a suburbanization of freight distribution facilities in large metropolitan regions in the US and abroad, such as in France (Cidell 2010; Dablanc and Rakotonarivo 2010; Dablanc and Ross 2012). That said, this trend has not been as dramatic in smaller metropolitan areas in the US or Canada, in part because of greater land availability near existing port facilities, such as in the Seattle region (Dablanc, Ogilvie, and Goodchild 2014; Woudsma and Jakubicek 2020).

The suburbanization of freight facilities has been enabled by the relatively low transportation costs of containerized shipping. Freight carriers choose to invest in large freight terminals based more on land availability than transportation costs, which represent a small share of the shipping costs (Dablanc and Ross 2012). But this has meant longer trips, an increase in traffic congestion, and higher levels of carbon emissions (Woudsma and Jakubicek 2020).

Freight decentralization is occurring at a faster rate than that of jobs or residents (Woudsma and Jakubicek 2020). As warehouses and distribution facilities locate far from existing centers, they may become new centers in themselves, attracting people who want to live in areas close by. This could have long-term impacts on residential and commercial land uses, further encouraging sprawl. As we saw in the previous highway section, this sprawl could, in turn, be associated with less accessibility for people with low incomes and people of color, who are less likely to be able to move quickly to be adjacent to such employment. This process of continual decentralization has encouraged land consumption and required a large share of the population to travel greater and greater distances to meet the demands of daily life, including going to work, school, and recreation. Increasing travel in and of itself produces higher levels of both carbon and particulate pollution. Sprawling land uses may also reduce investment in city centers, though these trends could have the opposite effect, too, such as by encouraging reinvestment in neighborhoods abandoned by the freight industry.

These changes are location-dependent. Communities where travel by foot, bike, or transit was already rare likely experienced less change with the rise of containers than did communities where such options are readily available. Meanwhile, central port areas in high-income cities where there is a strong market for renovation (such as in lower Manhattan) have evolved in a different fashion than areas in low-income cities where there is less interest in reconstruction as industries evolve.

Tertiary impacts: Truck-oriented retailing—then e-commerce flows

The rise of containerization has had effects on other aspects of the economy. Freight containers and the logistics chains that accompanied them have influenced the flow of retail trade. There have been two primary impacts, which we highlight here: First, the rise in big-box retailing, and second, more recently, the rise in direct-to-consumer e-commerce, both of which impact land use.

Big box retailing means chain stores' use of large-format spaces, typically at the urban edge and in single-story buildings surrounded by parking. This type of store, epitomized by Walmart, relies on the logistics distribution chain established through containerization. The concept was developed in the 1950s and 1960s but exploded throughout the US in the 1980s. These stores rely on distribution from ports and could not have been developed as easily in the pre-containerized freight period (Hesse 2008).

Big box stores are not necessarily located adjacent to distribution centers; indeed, most business in areas near freight terminals is unrelated to those centers (McCalla, Slack, and Comtois 2001). But big box stores are mostly located in urban areas to attract business from a large nearby population. And they, like the distribution centers, need access to cheap, automobile-accessible land. As such, they are typically at the urban edge (Sciara, Lovejoy, and Handy 2018).

The rise of such stores has had some impacts on land use. First, their development required use of previously natural or agricultural land and has, yet again, reinforced the monofunctional, automobile-dependent built environments characteristic of suburbanized development. At the same time, big box stores have likely impacted preexisting smaller businesses. Since the 1970s, large chains have come to dominate the US general merchandize retail market (Basker, Klimek, and Van 2012; Sampson 2008). Smaller stores have suffered from a loss of business over time (Sciara, Lovejoy, and Handy 2018), though changes are location-dependent (Stainback and Ekl 2017). Big box stores have contributed to the difficulty of historic downtowns in maintaining retail, as such, and reduced their vibrancy over time. At the same time, those new stores have given residents access to lower-cost goods—with researchers mixed on their impact on employment (Golden et al. 2006).

More recently, the rise of direct-to-consumer e-commerce threatened the big box model. The continuously declining transportation costs made possible by larger container ships, coordinated intermodal logistics, and just-in-time delivery have allowed retailers to skip stores altogether and ship goods to peoples' doorsteps (Rodrigue and Slack 2020). Since the advent of e-commerce, the number of deliveries throughout the US has more than tripled (Holguin-Veras et al. 2021).

This trend—also enabled by containerization—has unclear land-use impacts. It may mean that the inner-city areas, previously further from retail access (in big boxes and malls), become increasingly appealing because of easy access to goods. Or, alternatively, it may mean increasing interest in living in places even further from traditional retail areas, as goods become accessible to virtually everyone in a short period. Time will tell.

The containerization–land use feedback loop

We have explored the mechanisms by which containerization has impacted land uses—and the way land uses have influenced the shape of the rollout of containerization. In figure B.5, we describe the interconnected relationships between containerization and the built environment. These relationships are theoretical and also relate to other trends, such as the simultaneous construction of highway infrastructure.

Figure B.5 The Transportation–Land Use Feedback Loop, in the Context of Containerization

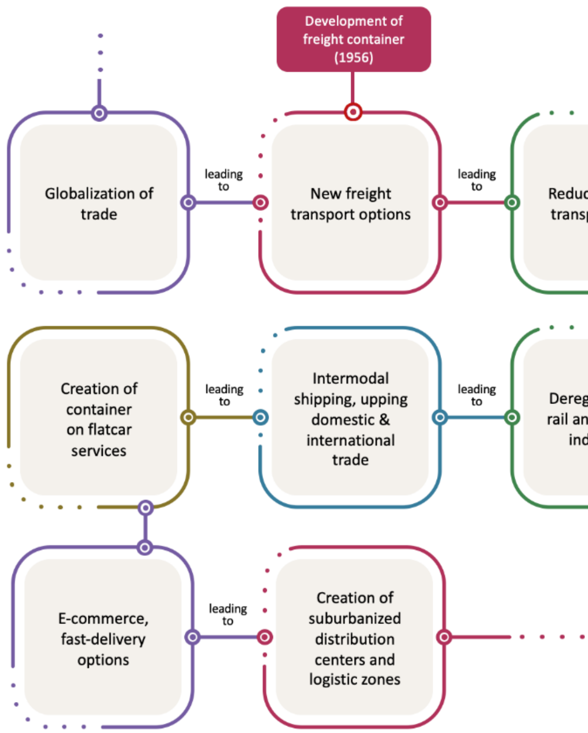


Figure B.5 is a simplified view of the links between technology and land use that begins with globalization—though that process, too, was set off by its own set of trends. Globalization expanded trade, encouraged by the development of the container. The container expanded accessibility by reducing freight transport costs, but required changing land uses, such as through the development of new port infrastructure on large, flat sites.

This new port infrastructure allowed larger ships and expanded cross-oceanic trade, which, in turn, encouraged the development of new multi-modal freight, such as container on flatcar rail shipping. This advance, in turn, upped trade volume due to the possibility of eased inland shipping. Political officials in the US responded by deregulating rail and trucking industries. The proliferation of shipping companies that resulted expanded demand for one-story distribution centers, which themselves accelerated the creation of advancements in freight technology, such as double-stacked railcars and automated terminals. The improved logistics that followed facilitated the rise of e-commerce and other fast delivery options, which, finally, have themselves boosted the further creation of logistics zones, a new sort of exurban land use. This cycle of path-dependent feedback loops continues today.

The chain of path dependencies illustrated in figure B.5 was mediated through private market demand and public-sector intervention. Surely the rise of globalization and steady rise in freight demand reflects a latent interest in faster, more affordable access to consumer goods. Peoples' responses to cheaper and cheaper products were to buy more of them—and this reaction provided the momentum for the continual growth in the cargo-carrying industry.

The public sector's decisions influenced the course of this transportation-land use feedback loop. The decision of authorities to invest in container ports—combined with investments in highways—made it feasible to shift rapidly from largely domestic supply chains to internationalized ones. The deregulation of freight shipping carriers deconcentrated the storage and distribution of cargo, encouraging the logistics sprawl that is now commonplace.

Public authorities, finally, mediated the secondary impacts of containerization. In describing the impacts of a Target store in Davis, California, Sciara, Lovejoy, and Handy (2018) note that public initiatives supporting enlivening of the downtown area helped ensure that the Target store did not result in the failure of business activity in the central area. Rather, public support allowed the neighborhood to thrive in the face of this suburban competition.

What would an alternative universe look like?

The role of public-sector decisions in the process of freight containerization raises a question: Had public authorities acted differently, would the impacts of containers be felt differently? Some evidence from the US and abroad suggests such alternative outcomes were, or are still, possible.

Consider the differences in freight logistics in the Los Angeles versus Seattle regions. In the first, warehouses sprawled out between 1998 and 2009 with intermodal commerce (Dablanc, Ogilvie, and Goodchild 2014). In the other, distribution centers barely budged from their central location. In this case, the state of Washington's growth management strategy, which encourages infill development rather than suburban construction, played a role (Dablanc, Ogilvie, and Goodchild 2014).

Such planning, however, requires regional coordination. Dablanc and Ross (2012) examine conditions in the Atlanta metropolitan area, showing that differences in choices made by municipalities have contributed to inefficient warehouse locations that increase carbon emissions, congestion, and land consumption. One county official they interviewed noted that "we love planning but some other counties do not, and are ready to accept anything without any care given to conflicts of use, environmental justice or transitional planning" (Dablanc and Ross 2012: 438). As such, even if some localities wanted to support centralized logistics centers, or centers located in such a way as to reduce truck traffic, they were blocked by the more *laissez-faire* choices of their neighbors.

Holguin-Veras et al. (2021) point out that unmanaged logistics sprawl has expanded truck travel beyond what would be ideal if shipping were planned effectively. The private sector's focus is only on private costs and their decisions about locating facilities in sprawling locations derive from the fact that they will only consider central areas if "the savings in transportation costs are larger than the increment in land costs" (Holguin-Veras et al. 2021: 7). Though policymakers often lack adequate models to estimate the impacts of technologies (McLeod et al. 2019), this finding suggests that there is a potential benefit in public planning to address some of the negative externalities produced by containerization.

Indeed, examples from outside the United States suggest how this might be accomplished. In studying logistics activities planning in the Netherlands, Visser and Hassall (2010) show that that country concentrated cargo facilities in places that minimized truck travel while still ensuring fast delivery. They argue that this required proper zoning of industrial areas, local consolidation centers, a local network for urban delivery, and a multi-modal long-distance network. But this sort of planning "requires quite strong governmental intervention otherwise a large number of mini-terminals, business parks with freight, or just large numbers of independent large carrier depots will emerge" (Visser and Hassall 2010: 6066). This outcome appears to have occurred in most US metropolitan areas.

Implications for the AV ecosystem

What conclusions can we take from the experience with containerization that could apply to the AV ecosystem? First, many of the trends that we drew out from containerization likely will apply to AV systems when it comes to freight. If AV trucking reduces the cost of transporting goods, it may continue to accelerate the sprawling out of logistics facilities and warehouses that has marked the freight system since the rise of containers. This could encourage further carbon emissions and destruction of agricultural or natural land to provide the facilities for the single-story distribution centers that are key to modern logistics. Indeed, AVs could encourage further decentralization of distribution into a new geography of logistics, often far from ports. AV freight services could reinforce emergent trends of such facilities being located even further from urbanized areas, sometimes in virtually unpopulated communities. This would be enabled by the low labor requirements of AV freight systems.

Second, the history of containerization points to the fact that this new technology enabled new services, most importantly through the recent rise of e-commerce. This suggests that AV technology could set off a chain of new freight options that transform the ability to deliver to different locations throughout metropolitan areas. For example, AV service providers might eventually provide small-scale cargo deliveries using small vehicles that enable small business to thrive in dense urban zones.

Finally, the history of public involvement in mediating the impacts of containerization suggest, too, that the AV ecosystem's impacts are likely to be influenced by regulatory and investment choices made by governments at all levels. These governments can shape AV rollout, encouraging it to take certain forms and setting off a chain of path dependencies (figure 2.8).

Bicycle sharing

Over the course of the past two decades, cities worldwide have adopted bike-sharing programs, designed to offer riders the opportunity to rent bikes on a short-term basis for short- to medium-distance travel. Our review of scholarship shows that levels of bike use are directly associated with land-use patterns, and that the effectiveness of bike sharing programs—in terms of their encouragement of bike use and the promotion of social equity and environmental sustainability—can be determined by the existence of compact, dense, mixed land uses, combined with quality biking infrastructure. Although bike sharing has the potential to offer a low-cost transportation option, because of political choices about investments, those communities with access to them are more likely to be populated with residents who are wealthier and more likely to be White than their encompassing city. Furthermore, researchers have not conclusively demonstrated that bike sharing offers positive environmental benefits. Even so, bike sharing has played a role in local government choices about modifying street design and curb management, and these outcomes can offer lessons for AV rollout.

What is bike sharing?

Bike sharing refers to programs that provide short-term bicycle rentals, sometimes accompanied with technology to track rider movement (Fishman, Washington, and Haworth 2013). The idea is to provide access to environmentally sustainable transportation without burdening users with the cost of private ownership (Shaheen, Guzman, and Zhang 2010). These programs are self-service and usually offer pick-up and drop-off stations; the fare for a bike share trip typically covers the shared cost of bike purchase and maintenance. Proponents of bike sharing note that it can provide public health benefits from physical activity while improving environmental sustainability by shifting people out of cars and thus reducing congestion and emissions.

Since the 1960s, cities have instituted different forms of bike sharing (DeMaio 2009). Early efforts failed to take off because of a lack of technology for tracking or storing bikes; recent approaches have been more successful. Researchers categorize the development of bike sharing into four generations:

- **First generation:** Amsterdam's short-lived White Bike program is considered the first bike-sharing program in the world. Activist groups painted a few bikes white and placed them throughout the city for people to use freely. The lack of a security and tracking system meant many bikes were later found dumped into canals or taken for private use (DeMaio 2009).

- **Second generation:** This generation operated through coin-deposit systems for pick-up and drop-off at designated locations. Copenhagen launched the first large-scale program of this kind, but also faced vandalism and theft due to the system's anonymity (DeMaio 2009).

- **Third generation:** Bike sharing programs grew with technological improvements, such as electronically locking racks or bike locks; smartcards or mobile phone access; and telecommunication systems. They took hold first in European cities such as Paris and later in cities throughout the United States and China. Modern bike-share systems incorporate this technology to make it easier to rent; track (e.g., through GPS systems); and price (e.g., dynamic pricing through GPS technology and integrated payment systems) (DeMaio 2009).

- **Fourth generation:** The latest generation of bike sharing incorporates the technology from the third generation, but offers free-floating options, which do not require docking (Zhao et al. 2020). An additional, coinciding technological development is the electric bike. Bike sharing programs with electric assistance allow riders to exert less effort and are increasingly common in both third and fourth generation bike share systems (Fishman and Allan 2019).

Today, there are more than 2,000 bike-sharing systems in the world operating close to nine million bikes (Fishman, Washington, and Haworth 2013; The Meddin Bike-sharing World Map 2022). Nonprofits ran many of the first bike sharing programs, but today key providers of bike sharing are governments, quasi-governmental transport agencies, universities, non-profits, advertising companies, and for-profit organizations. Typical funding sources include advertising, user fees, and local public funds (Ricci 2015; Shaheen, Guzman, and Zhang 2010). Many bike sharing systems have multiple providers playing different roles; a city government may create a program, for example, then hire a private company to manage day-to-day operations.

Bike share technology-land use connections

There is growing evidence on the determinants of bike-share usage, many of which are tied to urban land use. Above all, bike-share users are motivated by reductions in travel time and costs (Buehler and Hamre 2014). Land-use conditions are more influential on bike-sharing use than vice versa (meaning there are few measured impacts of bike sharing on land uses). This may result from the fact that land-use changes take time to manifest—or that bike-sharing simply has few impacts on land-use outcomes.

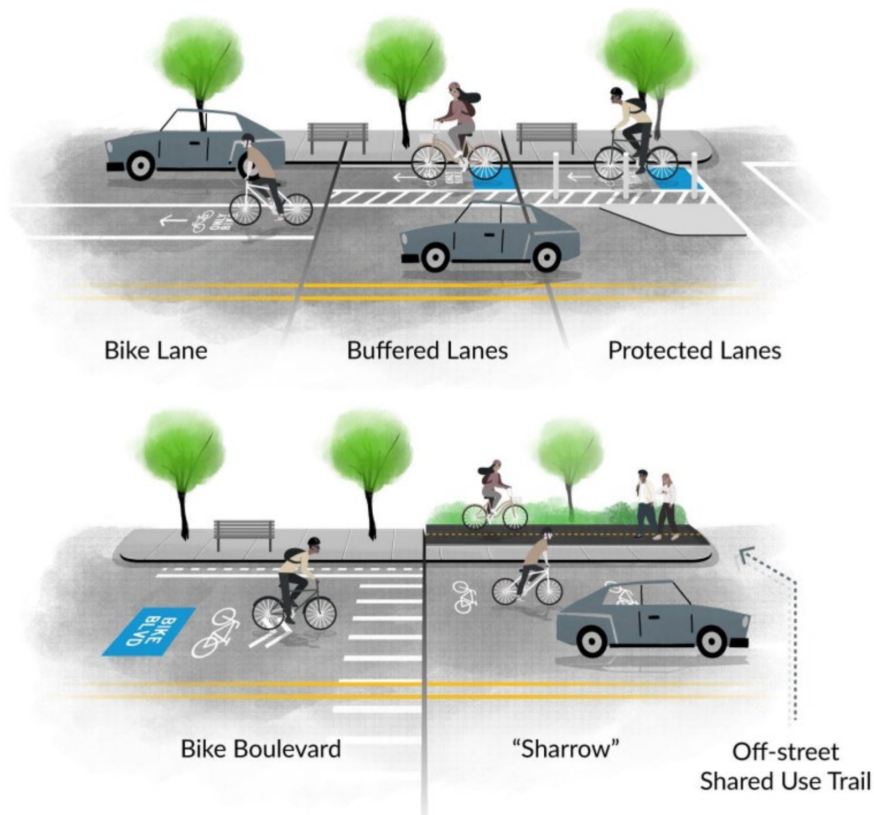
The use of privately-owned bikes and bike sharing have similar connections to land use, as users generally prefer these options as a short-distance transportation mode. Privately-owned bikes and electric bike sharing generally allow longer journey lengths than non-electric bike sharing systems; private bikes offer greater independence and ease of handling, and electric bike sharing allows users to exert less physical effort (Castillo-Manzano, Lopez-Valpuesta, and Sanchez-Braza 2016; Uteng and Uteng 2021). Researchers view these as complements rather than substitutes; depending on the desired trip length, users may consider one of bike options over another. Where possible, we make distinctions among these, though the land-use connections are difficult to separate.

Land use influence on bike-share systems

Zhao et al. (2020) propose a theoretical framework for understanding potential land-use impacts on bicycle usage. They argue that certain types of land uses (green space and commercial uses), a diverse mix of land use, and land-use connections (bicycle infrastructure and proximity to bike-share stations) promote demand, convenience, and perceptions of safety, which increase use (Bachand-Marleau, Lee, and El-Geneidy 2012; Eren and Uz 2020; Faghih-Imani 2014; Fuller et al 2011; Wang et al 2016). Bike use increases when transit stations are accessible, and transit use also increases when paired with bike accessibility (Brons, Givoni, and Rietveld, 2009; Pucher and Buehler, 2012). This suggests that bikes can serve as a first- and last-mile transportation option when paired with transit.

Since the risk of death and severe injury is considerably higher for cyclists than for motor vehicle occupants, safety matters for bike usage (Ding et al. 2020; Fowler, Berrigan, and Pollack 2017; Grasso, Barnes, and Chaves 2018). Bicycle safety can be partly explained by driver behaviors, but it is most improved through the provision of protected bike lanes (Bhuyan et al. 2019; Fishman et al. 2012). Bicycle infrastructure, such as protected bike lanes (Figure B.6), bike lane connectivity, and nearby retail destinations has strong connections with bicycle usage (Ma and Dill 2015; Titze, Stronegger, Janschitz, and Oja 2008). Safety, moreover, is a core consideration for bike-share use. A study of bike-share users in Washington, DC found that bike-share ridership and the presence of bike lanes—providing increased safety for users—have a statistically significant, positive relationship (Buck and Buehler 2012).

Figure B.6 Cycling Infrastructure Types



Source: Freemark et al. (2022).

Best practice for implementing bike-sharing programs recommend placing bike-share stations on sidewalks that near transit, major cultural or tourist attractions, major public spaces and parks, and along existing or proposed bike lanes (ITDP 2013). For example, Figure B.7 shows a busy intersection adjacent to Meridian Hill Park, a popular public space in northwest Washington, DC. The intersection has a protected, two-way bike lane that also serves as a crossing island to make it safer for pedestrians to cross the street. In the crossing island, there are also two bike racks. On the other side of the street, there is a large sidewalk space with docking stations for the city's Capital Bikeshare system.

Figure B.7 Protected Bicycle Infrastructure in Washington, DC

Source: Jorge Morales-Burnett (2023).

Bike sharing influence on land use

There is little research assessing the direct impacts of biking (or bike sharing specifically) on land uses. It is clear, however, that many local governments are reshaping the built environment to promote cycling. For example, many cities now require bike parking to be included in new development projects; several such ordinances have been passed since the introduction of bike sharing.[30] Localities are also engaging in street and sidewalk design, to foment more bike use. These street improvements respond to the robust evidence cited above about the impact of surrounding land uses on bike utilization rates.

Bike sharing increases competition for curb space because many cities have incorporated docking stations onto curbs (Marsden, Docherty, and Dowling 2020). Greater demand for street space for bikes is expected as more cities implement safer, bike-friendly infrastructure. Assuming cities choose to prioritize bike sharing, there may be increased pressure to expand these features further—thus further increasing competition for space. Indeed, bike sharing schemes have been most successful where they were instituted along with direct improvements in bike infrastructure (Ricci 2015).

Docking stations can have various configurations, but a standard 15-dock configuration can be 40 feet long and 6 feet wide, either on the street, on the sidewalk, or in open spaces such as parks, plazas, or parking lots (NACTO 2016). This requires that cities trade off space with other uses; on-street stations replace car parking and sidewalk and open-space stations require sacrificing pedestrian space. An analysis of on-street docking stations in New York City found that seven CitiBike stations holding 283 bikes replaced 41 parking spots (Peters, Davidson, and Santiago 2015). Figures B.8 and B.9 show how the Capital Bikeshare system in Washington, DC has integrated docking stations on sidewalks while maintaining space for pedestrians.

Figure B.8 Capital Bikeshare docking station in Washington, DC

Source: Jorge Morales-Burnett (2023).

Figure B.9 Capital Bikeshare Docking Station in Washington, DC

Source: Jorge Morales-Burnett.

Whether privately owned or operated through public bike-share systems, dockless bikes also put pressure on curb space (Fishman and Allan 2019). As the supply of dockless bikes and other forms of micromobility such as e-scooters grew, local governments and the public became increasingly concerned about users parking them in a haphazard fashion, raising perceptions that they were intruding on the pedestrian public realm. As Fishman and Allan (2019: 132) note:

> Docking stations signal to the public that shared bikes belong within the space afforded by the station… Dockless bikes, on the other hand, are rarely afforded any rights to public space. The idleness of an individual dockless share bike is obvious without a designated parking location. This leaves dockless bikes as 'matter out of place' within the public realm and open to criticism when bikes have been left unused for a period of time.

As such, some researchers have recommended strong coordination with local governments to provide designated parking spaces for dockless bikes (Fuller, Waitt, and Buchanan 2018). Parking for these bikes such as bike racks or even signposts can take up less space than docking stations (see figures B.10–B.12). Other forms of micromobility also use these parking means and can increase demand for limited space (figure B.11), especially as some local governments require locking vehicles instead of leaving them anywhere on the sidewalk.[31]

Figure B.10 Two Bike Racks Taking Up One Car Parking Spot in Washington, DC

Source: Jorge Morales-Burnett (2023).

Figure B.11 Bike Racks in the Sidewalk Near the Curb in Washington, DC

Source: Jorge Morales-Burnett (2023).

Figure B.12 Bike Attached to Street Parking Sign in Washington, DC

Source: Jorge Morales-Burnett (2023).

Research assessing the impacts of bike-sharing on land use is almost non-existent, possibly because land-use changes take years to manifest and bike-share systems are relatively new. Since there is evidence showing that bike share mostly encourages users to shift away from other sustainable modes such as public transit and walking, which may have similar land-use effects, the contribution from bike share toward changes in land use may be insignificant (Fishman, Washington, and Haworth 2013).

Another possible reason why bikes as a general mode of transportation have yet to have a major impact on land uses is because biking is heavily influenced by weather conditions and the natural environment. Transportation modes that are less affected by these natural conditions may be more consistently used and therefore have stronger influences in shaping land use (El-Assi et al. 2017; Gebhart and Noland 2014; Kutela and Teng 2019). That said, the requirements that new buildings include bike parking, as noted above, do represent a change in building form.

Bike sharing and its relationship with social and racial equity

Some scholars assert that bike sharing has equity benefits. It is a low-cost transportation mode relative to private ownership of cars or even bikes. When comparing cyclists who own bicycles to those who use bike-share, researchers found that bike-share users had lower incomes and were more likely to be women and younger (Buck et al. 2013). However, when compared to the general population, bike-sharing users tend to be wealthier, more educated, and younger, and are more likely to be White and male (Grasso, Barnes, and Chaves 2018; Ricci 2015**).** Active transportation plans have often inadequately integrated the needs of residents with lower incomes and communities of color, largely targeting middle and higher income neighborhoods for improvements and failing to consider access gaps between low and high income areas (Martens, Golub, and Robinson 2012; Scott, Oh, and Lei 2015).

The built environment is a key contributor to these variable outcomes. The location of bike-share stations has been less likely to be in high-poverty neighborhoods with high proportions of residents of color (Smith, Oh, and Lei 2015; Ursaki and Aultman-Hall 2015).[32] A survey of Brooklyn, Chicago, and Philadelphia residents shows that lower-income residents and people of color do not use bike-sharing systems as much as higher-income White residents, even though they may be just as interested in using them; this may result from inadequate local infrastructure (McNeil, Broach, and Dill 2018). Evidence suggests that if bikes are made more accessible to residents, they will use them at higher rates. For example, research about Minneapolis-St. Paul and London, UK found that people residing in neighborhoods with higher concentrations of minority residents and with lower socioeconomic status take more bike-sharing trips after controlling for various accessibility factors, as well as gender and age (Oglivie and Goodman 2012; Wang and Lindsey 2019).

Other socioeconomic factors beyond infrastructure influence these trends, such as the cost of renting a bike, the system's dependence on credit cards and smart phones, a lack of reliable internet access, and lack of familiarity (McNeil, Broach, and Dill 2018). Furthermore, structural problems may be at play; perceptions of crime in low-income neighborhoods can diminish peoples' willingness to bike (Lusk et al. 2021). In the US, bike-share system operators have noted that price is a principal barrier for low-income communities to access bike share and have implemented reduced pricing schemes in some cases (McNeil, Borach, and Dill 2018).

Given these patterns and the tendency of some cities to disproportionately invest in middle- to high-income neighborhoods, when investments in bike infrastructure are made in lower-income neighborhoods, residents sometimes perceive them as signs of gentrification (Hoffmann 2016). However, there is evidence to suggest that the impacts on socioeconomic status in a neighborhood after the installation of bike facilities are statistically insignificant (Ferenchak and Wesley 2021). Dockless bike sharing shows potential for lowering reliance on stations and thus could offer more equitable access. But one Seattle study shows that these "dockless" bikes are still more likely to be concentrated in areas with higher incomes and educational attainment (Mooney et al. 2019).

Bike sharing and environmental sustainability

One benefit of bike sharing shared by its proponents is their potential to reduce emissions (DeMaio 2009). Evidence to support this argument, however, has been limited. Many studies suggest that modal shift toward bikes is mostly from other sustainable transportation modes such as public transit and walking, rather than driving (Fishman, Washington, and Haworth 2013).

This is not to say that bike sharing cannot substitute for car use. One study in Dublin, Ireland found that 80.2 percent of bike-share users shifted from walking, bus, and rail, with the remaining 19.8 percent previously having driven (Murphy and Usher 2015). The modal shift from higher-income earners tends to be from car or rail, and for low-income earners from bus or walking. In other contexts, rates of car substitution are lower, such as in Montreal, where only 2 percent of bike-share users switched out of private cars (Bachand-Marleau, Lee, and El-Geneidy 2012). One study even found that, given the low substitution rates from cars, bike sharing could potentially *increase* emissions when accounting for the use of vehicles to redistribute the bikes—the process of shifting bikes across stations to balance the number of bikes available in the network (Fishman, Washington, and Haworth 2013).

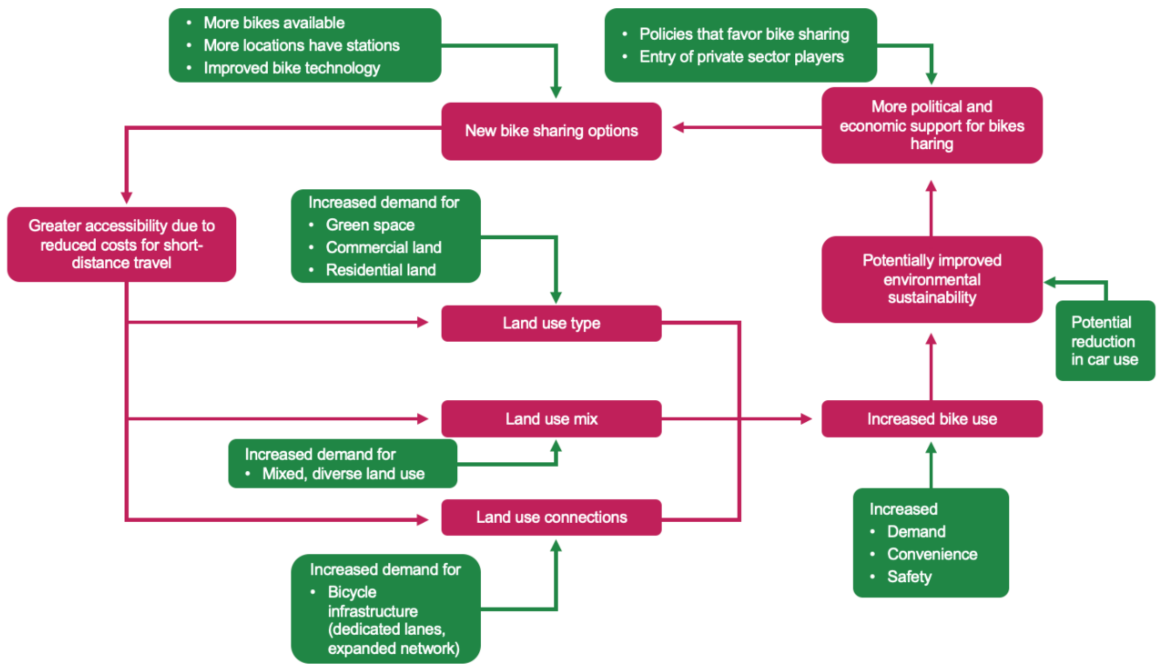
When specifically examining shared electric bikes, the impact on the environment likely varies from city to city. But a few studies have noted that electric shared bikes have a positive impact on the environment, especially in areas that are less dense, less diversified in land use, and with populations that have lower incomes (Li, Fuerst, and Luca 2022). Long trips taken on electric bikes from less dense areas are more likely to replace car use (Fukushige, Fitch, and Handy 2021; Sun et al. 2020).

Still, there is inadequate evidence on the influence of bike sharing on the frequency of car trips, which, if explored, could illuminate in greater detail the extent of environmental benefits captured (Ricci 2015). There is some self-reported survey data suggesting that bike sharing reduces overall car use (Shaheen et al 2012). Moreover, cycling is an environmentally sustainable mode of transportation. Finally, there is evidence that bike-sharing availability promotes more bike trips; this, in turn, could normalize using bikes as a regular, reliable mode of transportation (Fuller et al. 2013).

The bike sharing–land use feedback loop

Although the links connecting land-use conditions and the use of bike sharing have been more documented by scholarly evidence than the link heading in the opposite direction, there is enough anecdotal data to suggest that a land use–transportation technology feedback loop is at play with bike sharing. Using the theoretical framework proposed by Zhao et al. (2020) on the impacts of land use on bike use, we expand the framework to close the loop (figure 2.16).

Figure B.13 Feedback Loop Between Land Use and Bike Sharing



Certain land-use types, the mix of those land uses, and land-use connections (bicycle-oriented infrastructure and proximity to bike-share stations) have positive influences on bike use. As bike use increases, demand for bike-sharing options rises, and bike-share operators work to meet that demand, as locating bike-share options based on those land-use categories is associated with system profitability (Shaheen et al. 2012; Shaheen et al. 2014). Bike-sharing options are expanded in the form of more bikes, more stations, and improved technology, which either increase the capacity for biking in bike-accessible locations or increase the accessibility of bike sharing in previously inaccessible locations. Greater accessibility to low-cost bike-share options would then increase pressure on localities to encourage land uses that support a city where more people want to ride bikes. And the loop thus can repeat.

The environmental impacts of this feedback loop depend on the degree to which bike-sharing can substitute for cars; the effectiveness of bike-share on this front remains unclear. Given connection between land use and bike use, changes in land use that make short-distance travel using bikes a more convenient alternative than cars is key. As land use is modified to be more compact, walkable, and bikeable, it is possible that the environmental benefits from bike-sharing will become more evident.

What would an alternative universe look like?

Bike use is tied to transportation and land-use conditions. In the US, policies that have prioritized car-oriented development over other forms of transportation—such as investments in building highways, demolishing dense, walkable neighborhoods, and subsidizing sprawl—have encouraged the creation of segregated, disconnected, unequal cities. In the present context in most US metropolitan areas—destinations being located far from one another and limited availability of safe cycling infrastructure—the ability of bike-sharing services to increase ridership significantly will be severely hindered.

In an alternative universe in which cities did not demolish neighborhoods for the sake of new highways, more sustainable modes of transportation such as public transit and bikes would have been more attractive as forms of mobility. Cities may have been less segregated, and once bike-sharing were introduced, gaps in access to it could have been smaller. A city with more pedestrian- and cycling-friendly land uses would have encouraged more use of active transportation—and residents would have been healthier, replacing car trips with other, more environmentally friendly modes.

Bike sharing's implications for the AV ecosystem

The context of bike-sharing related to AVs is in terms of the reconfiguration of streets and curbs, especially if AVs were rolled out as shared vehicles. Just as cities have been reimagining ways to redesign streets to incorporate bike lanes and share curb space so that bike stations are available, AVs may exert similar pressures. If AVs are shared, we can expect a greater need for designating pick-up and drop-off locations and potentially a reduced need for wide lanes that accommodate for human error (Wagner 2016). As with bike sharing, AVs are seen as a potential transportation mode to connect people to transit through the first and last mile of travel (Lau and Susilawati 2021). So, we can similarly expect demand for curb space around transit stations. The rollout of dockless bike sharing shows the need for close collaboration with local governments and a transparent framework so that everyone involved is aware of their rights and responsibilities, and so that AVs do not become a disamenity for the public realm.

In some cases, localities have promoted bike sharing through public policies related to development, such as related to parking requirements for new buildings. This has altered the form of buildings as they have become more welcoming of bikes. But this has required local actions. Similarly, we might see some local governments working to incentivize AV use in certain designated areas through geofencing. This could require active engagement on the part of local officials to prioritize the use of AVs rather than other types of cars.

Another area where we can expect similar trends, at least in the short term, is in terms of the inconclusive impact of the technology on the environment. Although AVs may reduce car ownership and run using electric propulsion, AVs may increase vehicle miles traveled by encouraging long –distance trips or inducing demand (Fagnant and Kockelman 2015). Here is a key difference, however, that can be drawn between bike-sharing and AVs. Bike-sharing reduces travel costs and eases travel, but generally only for *short-distance travel.* Bike-sharing is not expected to encourage urban sprawl, but AVs could. AVs are likely to be more versatile and support both short-distance and long-distance travel.

Finally, there may also be parallels related to infrastructure lock-in. Bike share is more prevalent in places with better bicycle infrastructure, and AVs (as a kind of personal automobile) may become more prevalent in places that are already designed around car infrastructure.

Ride hailing

Increasingly available since 2010, ride-hailing is a form of paid, chauffeured passenger vehicle service arranged via a website or app. By 2018, 36 percent of US adults had used ride-hailing, up from 15 percent in 2015, with most users concentrated in urban and suburban areas (Jiang 2019). The growth of the ride-hailing industry benefitted from significant private support, with private investment through venture capital upwards of $32 billion; it makes use of existing capital and infrastructure, privately owned passenger cars, and existing public roadways, combined with other car-focused infrastructure.

So far, the impact of ride-hailing on land use is limited compared to that of other transportation technologies. Based on our research review, this seems unlikely to change as the ride-hailing industry matures. There is no evidence that the availability of ride-hailing is a major factor in peoples' decisions about where to live or work, firms' decisions about where to locate, or cities' decisions about how to develop their road networks. That said, ride-hailing does impact land use on a smaller scale in the realm of street design: evidence shows that ride-hailing decreases demand for parking and intensifies demand for curb access. Both those dynamics foreshadow potential impacts of the AV ecosystem. Land-use patterns, moreover, are a determinant of the amount and type of demand for ride-hailing.

Context for ride hailing

Ride-hailing is a form of paid, chauffeured passenger vehicle service arranged via a website or app. This arrangement is mediated by third-party companies that match drivers with riders, establish prices, process payments, and offer routing and real-time tracking using GPS, among other services. In most cases in the United States, ride-hailing platform companies classify drivers as independent contractors who personally own/lease, maintain, and manage vehicles used for ride-hailing.

Ride-hailing is synonymous with ride-sourcing, and ride-hailing companies are sometimes called transportation network companies. Ride-hailing is sometimes used synonymously with ride-sharing, but we define ride-sharing specifically as the subset of ride-hailing services in which unacquainted passengers ride in the same vehicle during at least part of their respective trips, usually going to different destinations. Ride-sharing is sometimes referred to as "pooled" trip taking. Ride-hailing has been available since the launch of Uber services in 2010, before which there were limited options for pre-arranging taxis.

Several ride-hailing companies have subsidiaries that offer on-demand delivery of food or other items (e.g., UberEats), and other separate companies exist with this focus (e.g., GrubHub), both using a similar business model and app platform to passenger ride-hailing. This historical example focuses primarily on ride-hailing for passenger transportation, but these delivery apps have similar impacts on curb management and emerged from a similar regulatory and economic context.

Relevance to AVs

Ride-hailing offers important lessons for AV policy and planning because it shares several similarities with potential AV service options, namely:

- Private companies are the primary developers and owners of enabling technologies, and private investors provide the primary source of funding;
- No new vehicle designs, propulsion systems, fuels, or large-scale built environment infrastructure are *inherently* required to scale this technology (though some AV services may operate using purpose-built vehicles as they do not need equipment like steering wheels);

- Existing policies and regulations may apply to the technology, but it is unclear to what extent existing regulations are relevant; moreover, they may be poorly suited to manage the technology to promote positive environmental or social outcomes;

- The technology may provoke an increase in on-demand trips with user-specified times, origins, and destinations. This occurs in a context in which passengers do not own or drive the vehicles, leading to increased pick-ups and drop-offs, combined with decreased parking demand; and

- An increased role of digital technology in mediating use of transportation.

Impact on transportation costs

Ride-hailing may have reduced the capital costs of moving passengers, since it involves using existing capital (cars and roads) more intensively (e.g., unlike with personally owned cars, vehicles spend less time waiting for passengers). Experience, however, shows that ride-hailing is an expensive mode; its value proposition is a combination of decreased travel times, the ability to handle complex trips, and increased convenience or comfort. Ride-hailing costs passengers an average of $2.00 per mile, compared to $0.53 for personal cars, $0.20 for public transportation, and $0.36 for rental cars (Goldman Sachs 2019). Many predictions for the future of ride-hailing identify it as complementary to other modes and technologies ("The Future of Mobility in 2035" 2023; Walmsley n.d.), as opposed to transportation technologies like vehicle electrification, which may come to characterize every motorized vehicle. Indeed, a significant share of AV services may be operated through ride-hailing.

Public and private support

Ride-hailing companies benefitted from significant private investment. Over $32 billion in venture capital was invested in ride-hailing companies, excluding non-US companies and on-demand, last-mile delivery services (like GrubHub or DoorDash) ("Crunchbase" n.d.). Private investment has been an enabler of ride-hailing, since most ride-hailing companies have yet to generate net profits as of 2022.

Compared to other transportation technologies, on the other hand, ride-hailing has had limited *direct* public involvement, in terms of policy, regulations, or financial support. This is especially true of the technology in its earliest stages. Even so, in a broader sense ride-hailing has been enabled by a range of existing public infrastructure, investments, and sociotechnical systems that made its operating model possible. These public supports in the car-based mobility system, include roads, gas stations, traffic signals, driver licensing systems, various subsidies for private vehicle ownership and use, and more (Urry 2004); phone and internet networks and widespread access to smartphone and digital payment systems (Clewlow and Mishra 2017); and economic and regulatory support for technology companies, including tax policy of multiple levels of government (Qin-Liang 2022; Vogels n.d.).

Ride-hailing has been enabled by acceptance of peer-to-peer platforms, following companies like Airbnb and Zipcar. Ride-hailing, finally, capitalized on the growth of "gig" work, enabled by the erosion of US labor protections in recent decades. While the use of contract workers as drivers is not inherent to ride-hailing, it was critical to ride-hailing's current operating model, allowing companies to operate with lower labor costs and capital costs—since drivers use their own cars.

There are a few examples of more direct public support for ride-hailing. Some cities subsidize ride-hailing for certain users at certain times. In 2019, Washington, DC (temporarily) subsidized ride-hailing between midnight and 4 am to fill gaps in existing public transit (Siddiqui 2019). In 2022, Uber and Lyft were awarded a federal contract to simplify the process of providing transportation for work-related travel (Reuters 2020). Overall, however, these supports have not likely significantly increased ride-hailing use. Some governments were more likely to oppose ride-hailing than actively support it; Oregon banned it and New York City attempted a cap on cruising time ("In Win for Uber and Lyft…" 2019; Lowensohn n.d.). Some cities have developed regulation, licensing/permit schemes, and fee structures specifically for ride-hailing (BBC News 2022). While these impose some constraints on ride-hailing operations, they can be seen as supportive in that they formalize -hailing as a legitimate transport mode.

Links between ride hailing and land use

So far, the impact of ride-hailing on land use is limited compared to the land-use impacts of automobiles, highway systems, and streetcars; this fact seems unlikely to change as the ride-hailing industry matures. There is no evidence that the availability of ride-hailing is a major factor impacting peoples' decisions about where to live, firms' decisions about where to locate, or cities' decisions about how to develop their road networks (except for related to curbs and parking, as discussed below). More widely, since ride-hailing (in its current form) depends on the use of privately owned passenger cars, ride-hailing could be said to entrench a transportation system centered around passenger cars, with their attendant impacts on land use. We do not explore this in depth herein because those impacts are within the scope of the historical example on highways above. Therefore, after reviewing relevant literature on ride-hailing, we focus this case study on three sub-topics at the nexus of ride-hailing and land use:

- The impacts of ride-hailing on parking demand;
- The impacts of ride-hailing on the demand for and management of curb space; and
- How land-use patterns impact the peoples' choice to use ride-hailing versus other modes.

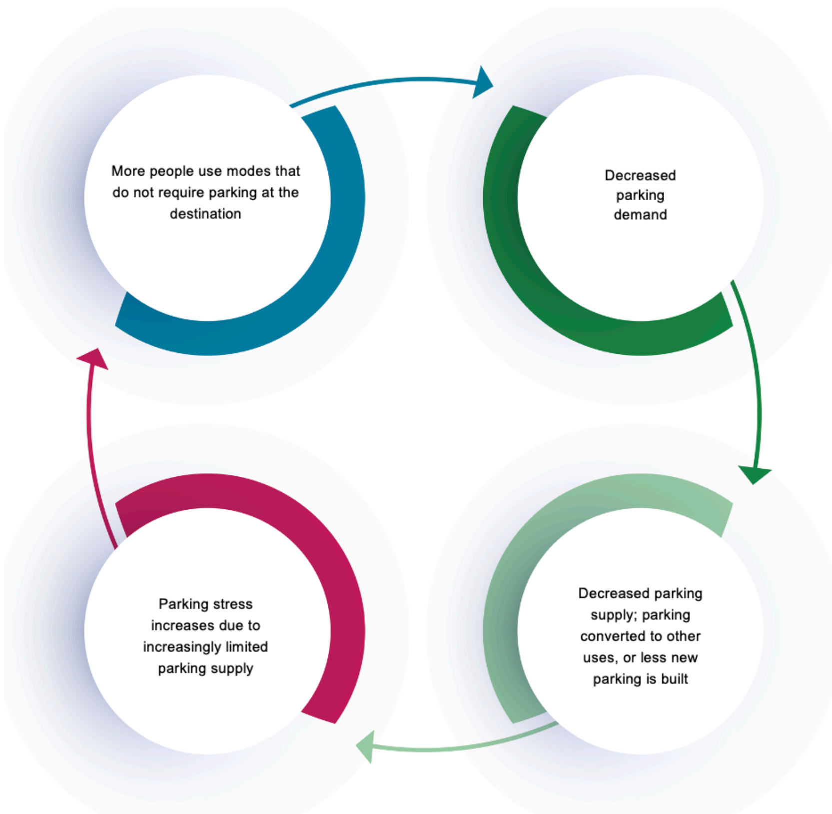
We made these selections because, based on our review of extant scholarship, we believe these to be the most significant links between ride-hailing and land use, and because they have relevance to AV technology. Even so, there are hypothetical impacts of ride-hailing on land use that have yet to be studied. For example, ride hailing may have encouraged development in entertainment districts in central cities that are relatively poorly linked to the transit system. These areas may have benefited by offering people a way to get home without driving themselves. Future research is needed to understand how ride-hailing may have impacted parking ratios in such areas.

Connections between ride hailing and parking demand

Ride-hailing decreases demand for parking in central urban areas and at locations that typically have large dedicated parking facilities, such as airports and stadiums (Wadud 2020; Zipkin 2017). The stress of parking in those areas, generated by the time required to find a parking spot and then travel to the final destination; parking costs; and uncertain or limited parking availability, are often reasons that passengers choose ride-hailing instead of driving (Henao and Marshall 2019). A 2017 survey of over 4,000 adults in major US cities found that 21 percent of adults use ride-hailing and 39 percent of those would otherwise drive (Clewlow and Mishra 2017). Henao and Marshall (2019) find that 37 percent of urban ride-hailing users cite parking issues as their top reason to use ride-hailing. Of ride-hailing trips that were induced by parking stress, about half were to the airport and a third were to event venues, restaurants, or bars. They estimate that roughly a quarter of ride-hailing trips would otherwise have been taken by car and required a parking space at the destination.

Theoretically, this could generate a feedback loop, as visualized in Figure B.14. Decreased parking demand from ride-hailing (top right circle) means parking space could be reduced or reallocated to other uses that have more positive environmental, economic, or social impacts, such as housing (bottom right circle) (Brown, Mukhija, and Shoup 2020). It could also support policy to reduce parking space, such as changing from parking minimums to parking maximums for developments (Bloomberg 2021). Parking availability (Guo 2013; Weinberger 2012; Weinberger, Seaman, & Johnson 2009) and cost (Hess 2001; Wilson & Shoup 1990; Wilson 1992) are significantly factors in car ownership and modal choice, so increased parking stress to decreased parking supply (bottom left circle) could contribute to decreased car ownership or use (top left circle), which would in turn further reduce parking demand (top right circle).

Figure B.14 Feedback Loop of Decreasing Parking Demand from Ride Hailing



These impacts on parking would only materialize if ride-hailing constituted a large modal share. With its current U.S. mode share (around 2 percent of trips), ride-hailing may be unlikely to cause nationally or regionally significant changes in parking demand or supply, or in car ownership (Mansoor n.d.; Bureau of Transportation Statistics 2017).[33]

Some could stand to lose out from decreased parking demand. It could decrease revenues of entities that generate a significant share of revenues from parking, including airports (Morris 2018; Steele 2018; Zipkin 2017). In response, some airports are charging fees to rideshare operators (which are sometimes passed on to passengers)—but these do not fully make up for the losses in parking revenue. Clark and Brown (2020) modeled projected parking revenue in Seattle, finding that parking revenue generated will continue to increase at current ride-hailing use rates but would decline if ride-hailing trips levels grew significantly. This has implications for managing a transition to AVs: the parking industry and governments with a significant share of revenue from parking may lose out in the transition, and therefore are important stakeholders to consider.

Connections between ride hailing and curb demand and management

One of the most significant intersections of ride-hailing and land use is at the curb. Ride-hailing and associated delivery services like Uber Eats are notable contributors to rising demand for curb access. Each ride-hailing trip involves picking up and dropping passengers, and drivers often need to pull over between passenger trips to accept their next trip or use their phones. Ride-hailing's role can be conceptualized more broadly: there has been an intensification and diversification of curb space use. Intensification describes greater demand for curb access, mostly from home delivery and ride-hailing; diversification refers to a growing number of users and uses for curb space, including on-street EV charging, car-share and, bike- and scooter-share (Jaller et al. 2021; Liu et al. 2019; Marsden et al. 2020).

Despite the intensification and diversification of curb demand, few cities have reallocated curb space to new uses or changed practices for managing access. Designated spaces for pick-up and drop-off are uncommon in urban areas (Marsden, Docherty, and Dowling 2020). In many places, governments lightly enforce curb regulations and encourage informal norms, often largely looking the other way. In the case of ride-hailing, this leads to frequent double-parking, or blocking intersections and bus stops (Kukura 2017; Novich 2020; Wenus 2017). This can be dangerous and stressful for drivers, passengers, and other roadway users who then face blocked lanes or crosswalks. It can put drivers in a difficult position, forcing them to choose between a possibly unsafe requested stop or a passenger becoming upset and giving them a bad rating. In the case of delivery via ride-hailing platforms, drivers risk receiving a municipal fine or ticket if they leave vehicles illegally parked to complete deliveries. Some ride-hailing apps are experimenting with a feature that suggests a safer or more accessible pick-up spot near a ride origin, but this practice is not widespread (Constine 2015; "Uber Pickup Spots" n.d.).

Given these challenges and externalities, why have governments been hesitant to change this status quo? Marsden et al. (2020) posit that governments' hesitancy to change curb management or enforce existing regulations results from the complexity of mediating between the many curb stakeholders with differing interests. For example, on a given nine-foot, curb-adjacent strip, residents with cars might prefer free, on-street parking; cyclists might prefer a protected bicycle lane; ride-hailing and e-commerce companies might prefer short-term drop-off zone, and so on. Marsden et al. (2020: 1) note that, "despite decades of debate about how to manage the allocation of space and time to different users, the curb remains a highly contested space which the state finds hard to govern effectively." An additional challenge is city governments' typical lack of information about what vehicles and users will need access to what areas, at what time, and for how long.

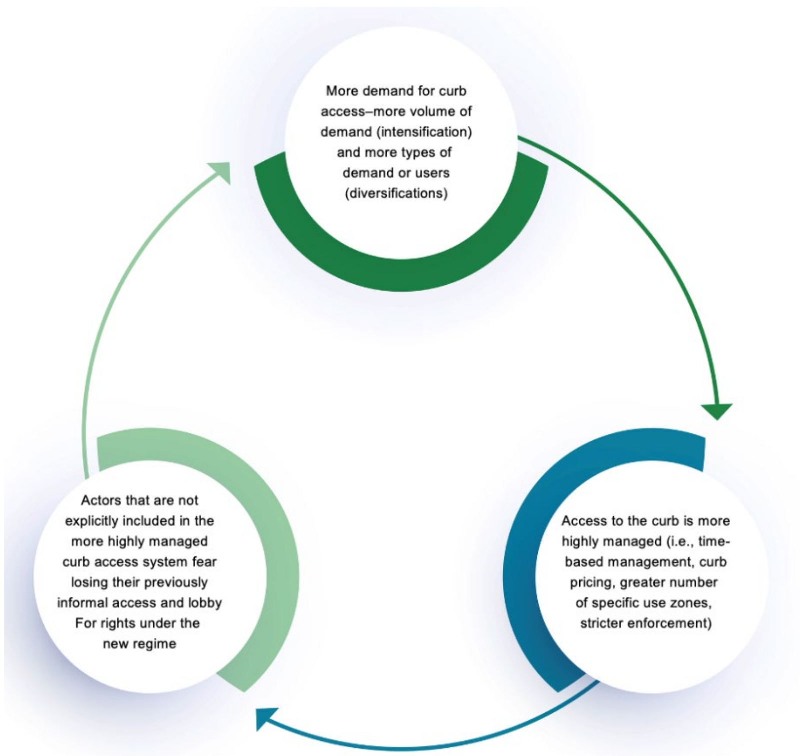
Marsden et al. (2020) note that taxi services also resist changing curb rules. This positioning could be seen as aligned with companies' incentives: The inconvenience of inconsistent curb access falls on individual ride-hailing drivers, while the benefits of flexible, free access to the curb accrue to companies (financially and in terms of regulatory burden) and their passengers (in terms of convenience). The status quo does have downsides at the company level, however: the accumulation of externalities could translate into worse public opinion of ride-hailing overall or make governments or regulators less supportive of it. Moreover, curb access is not always free. Some delivery companies, especially those with larger vehicles where the drivers need to exit the vehicle to deliver items indoors (e.g., PeaPod grocery delivery or UPS), receive frequent, expensive parking tickets and fines, which they price into their business model given the lack of viable, legal alternatives (Abrams 2017).

Some predict a digital, transparent, and dynamically managed curb space (Arup 2019). Already, some technology services give real-time insight on curb usage, communicate with potential users, and remotely enforce regulations. This could improve on today's approach to curb management. Time-based management could be separate from or complementary to curb pricing (Shoup 2021). Curb pricing is already widespread in the form of paid on-street parking, but charging for loading, unloading, drop-off or pick-up is uncommon, besides at some airports (Marsden et al. 2020). Since AVs may lead to more trips without parking, curb pricing could offset some lost parking revenue.

Some cities have begun moving in this direction. Washington, DC piloted an on-demand curb reservation system for commercial activity, including ride-hailing, food deliveries, and commercial deliveries (District Department of Transportation 2019) and has designed several ride-hailing pick-up and drop-off zones around the city (McFarland 2017). Boston, Fort Lauderdale, and San Francisco are experimenting with similar pilots ("Cities and Airports…" 2017; Clark and Brown 2020; Short 2019).

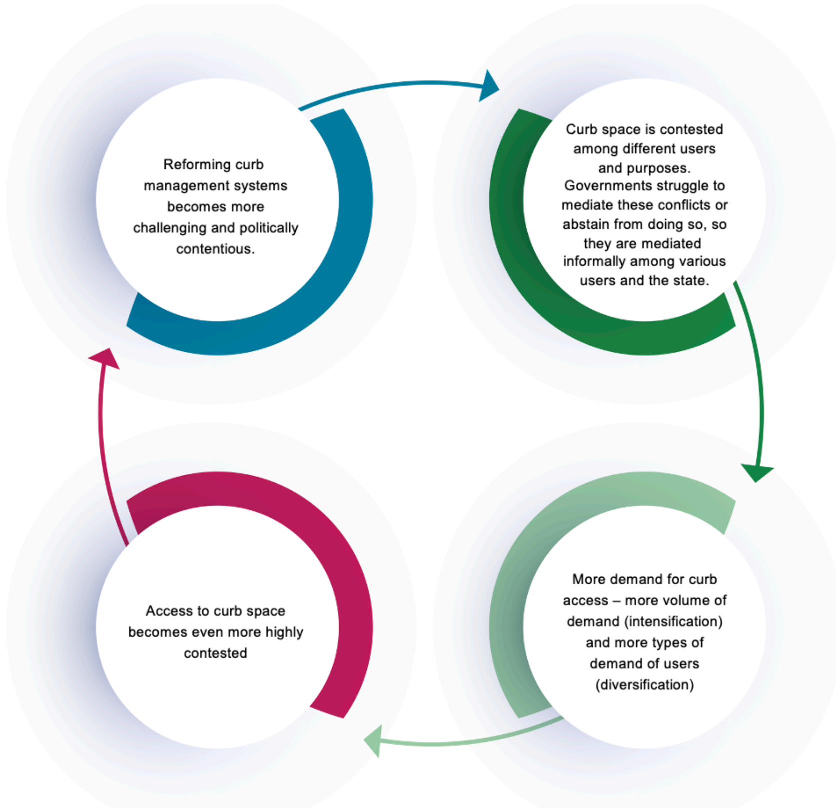
In figures B.15 and B.16, we illustrate two possible scenarios for the future of curb demand and curb management. Figure B.15 illustrates a first scenario in which increasing demand for curb access leads the public sector to more actively, heavily manage, and enforce curb access, in a system that could become increasingly complex as actors vie for codified, advantageous curb access.

Figure B.15 Feedback Loop for Managed Curb Access: Scenario One



In Figure B.16, increasing demand for curb access creates the opposite effect: increasing need for and contestation over curb access makes it more challenging and politically sensitive for governments to develop a new approach to curb management or enforce the existing system, entrenching a stalemate of light management and enforcement that coexists with informal, ad-hoc mediation by actors in each situation. Currently, neither feedback loop predominates. In some cases, they seem to exist side-by-side—for example, with specific and enforced regulations related to parking private vehicles but not personal bicycles.

Figure B.16 Feedback Loop for Managed Curb Access: Scenario Two



The impact of land use patterns on ride hailing

Land-use patterns are a determinant of the amount and type of demand for ride-hailing. Sabouri et al. (2020) found Uber demand to be correlated with more mixed land uses and higher density (of people, jobs, activities, and transit stops). Uber demand was positively correlated with intersection density and destination accessibility by both car and transit. Loa, Hossain, and Nurul Habib (2021) found that demand for public transit has a positive impact on the demand for ride-hailing services (and vice versa), and the demand for the two services is influenced by both built environment and zonal socio-demographic attributes. In other words, the same factors influence demand for both transit and ride-hailing. The most important determinants were the lengths of bus and streetcar routes and the density of non-residential land uses and destinations, especially health care/social services and retail.

Yang et al. (2022) analyzed research on relationships between land use and trips taken by taxi or ride-hailing and found that areas with greater densities and more mixed land uses had more trips by taxi or ride-hailing. A study of the determinants of shared ride-hailing (where unacquainted passengers are matched in the app to share their ride) in Chicago found that land use, trip characteristics, and rider characteristics were all predictive of the demand for shared rides (Dean and Kockelman 2021). Density of pedestrian and multi-modal infrastructure, longer trips (in time and/or distance), and areas with more retail and entertainment jobs were all correlated with higher demand for shared rides. Socioeconomic characteristics of origin zones with more shared rides included a higher percentage of unemployed residents, non-white residents, and young people, plus lack of vehicle ownership.

Ride-hailing enables a large degree of spatial dispersion in the "production" of transportation. Because ride-hailing is mediated by smartphone apps, there can be large distances between the offices (or remote workforces) that developed and managed the app and the business operations, the server warehouses that store associated data, and the locations of the driver and rider for a given trip.

Equity implications of ride hailing's impact on land use

Since ride-hailing has likely had limited impacts on land use, it has likely had limited impact on any population group or area. The primary beneficiaries of ride-hailing are its users, who enjoy an additional travel option that can offer faster and more comfortable trips than some public or active transportation modes or offer a ride free from parking stress or a designated driver. Those users largely live in urban or suburban areas, are younger, and middle- or high-income (Jiang 2019). Historical and ongoing racist land-use and transportation decisions have excluded certain people, especially people of color, from accessing economic opportunities that could put them in a position to now benefit from the option of ride-hailing (Stacy et al. 2022). In other words, historical discrimination and land use patterns mean that ride-hailing is typically not an affordable option for low-income people.

Non-shared ride-hailing does not produce large positive externalities; its negative externalities, meanwhile, are limited, primarily in terms of traffic congestion from added vehicle miles; safety hazards; and air pollution. If people bought vehicles exclusively or primarily to use to drive ride-hailing platforms, those vehicles would cause additional negative externalities, but research indicates that ride-hailing has not induced significant demand for additional vehicle purchasing (Lazer et al. 2021).

In examining employment-related equity impacts of ride-hailing, it is important to distinguish between drivers, who work as contractors, and the workers directly employed by ride-hailing companies. While the quality of driver jobs is contentious, the direct corporate jobs are more relevant to the AV transition. The spatial dispersion in the corporate "production" of ride-hailing, combined with the high level of consolidation in the industry (with just two companies dominating in the US) and a highly skilled and educated workforce, means the indirect local and regional economic benefits of the ride-hailing industry likely mostly accrued to more privileged workers in California's San Francisco Bay Area, where Lyft and Uber are headquartered. In the future, a more remote workforce and state-level corporate incentives could change that geographic distribution of ride-hailing's economic benefits.

Implications for the AV ecosystem

The emergence and impacts of ride-hailing affords several parallels to the predicted emergence and impacts of autonomous vehicles, which can inform proactive planning for AV deployment.

Public and private support

The extent of public support for ride-hailing shares similarities with AVs. Like ride-hailing, AVs would use existing public roadways and thus benefit from historical public investment. This is because, like ride-hailing, AVs are likely to iterate on existing vehicle types. Though AVs could involve new designs, AVs do not inherently entail new forms of propulsion, vehicle sizes, shapes, or dedicated infrastructure at the scale that was required for previous transportation technologies like trains (railway tracks), trolleys/streetcars (overhead catenary lines), or internal combustion engine vehicles (gas stations).

Similarly, like ride-hailing, most AV technology development has been conducted by well-funded private companies, including tech companies, automakers, and start-ups. They can raise and spend billions of dollars on research, even in the context of few opportunities for short-term profit generation and vague business models. In some cases, the short- and medium-term profit generation for AV companies is developing and selling software for Level 1 and 2 vehicle automation. Private companies and financiers are likely to remain major players in the AV space through all phases of roll-out.

Regulation

A key difference between ride-hailing and AVs is likely to be the sequencing of regulation and deployment. Many ride-hailing companies initially made their apps available without consulting local, state, or national governments, after which piecemeal regulations and policies were sometimes developed gradually, with large variations by place. This outcome may be less likely with AVs, though the state of public policy development on this issue remains unclear. Some regulation could come first, given factors like increased concerns about safety, an already long-running and highly publicized research process, the appetite for national and state regulation, the larger expected impacts on the existing mobility landscape and land-use patterns, and the possibility that AVs need more predictable roadway conditions and use patterns than the existing automotive fleet. AV-relevant regulatory takeaways from the introduction of ride-hailing (and micromobility) include:

- The propensity of private mobility companies to exploit regulatory ambiguity;
- That existing policy and regulatory frameworks are insufficient in managing new modes; and
- Users may acclimate relatively quickly to mobility technologies that are initially perceived as risky, whether that be getting in a car driven by a stranger or by a computer.

Parking demand

Ride-hailing's impact of reducing demand for parking spaces could foreshadow a similar trend related to AVs. AVs could likely entail a larger share of trips that are on-demand, with no parking needed at the origin or destination, but a greater number of miles without passengers between trips. Researchers are starting to use ride-hailing data to predict decreased parking needs associated with the advent of AVs. Konder et al. (2020) note the tradeoff between decreased parking and increased vehicle miles, which will become more important with AVs. These changes in parking demand could also be related to the development of entertainment districts that are currently poorly connected to transit systems.

Curb management

The impact of ride-hailing on curb demand are relevant to a future with more AVs. With a shift to AVs, informal curb management arrangements and quick, semi-legal drop-offs and pick-ups will no longer be possible. To successfully operate in complex urban environments, AVs could need much more specific rules and information about the availability of usable space, with extremely limited violations. The tensions in supply of and demand for curb access would have to be resolved in advance by the system instead of dynamically and informally mediated by users, companies, and the public sector. Formalizing access to curb space would be an opportunity for the loudest, best-organized, or best-resourced stakeholders to shape regulations in their favor. This risks prioritizing the interests of commercial business (e.g., delivery, taxi, and ride-hailing) at the expense of less organized or politically powerful groups like pedestrians.

Modern electric vehicles

Electric vehicle (EV) technology—powering vehicles with batteries, allowing them to avoid internal combustion engines (ICE)—is century-old but has seen a recent resurgence. EVs, paired with renewably sourced energy, have the potential to mitigate climate change with reduced greenhouse gas emissions. As they do not emit tailpipe pollutants, they could have positive impacts on air quality. At the same time, EVs could exacerbate negative externalities created by ICE vehicles, such as sprawl and road fatalities. Additionally, due to their requirements for rare materials such as cobalt and lithium, and since they require charging infrastructure, they have the potential to create new challenges for society—and by extension for governance—as a result of land and water pollution and increased competition for scarce urban land. Government support for EVs has existed since the 1970s gas crisis, but more recently the US federal government has significantly expanded consumer tax credits to accelerate technological adoption. This support, which has encouraged rapidly increasing EV use, could be paralleled in the context of AVs, depending on public priorities.

Defining electric vehicle technology

When referring to EVs, we focus on battery-electric vehicles (other types of EVs could rely on other sources of power, such as catenaries, for propulsion, as do streetcars). At its core, an EV consists of:

- A battery that holds an electric charge;
- An electric motor that uses the electricity held in the battery to propel a vehicle; and
- The infrastructure needed to charge the battery.

Although there has been renewed interest in—and development of—EVs over the past few years, the technology has been around for over a century, dating to the same time the conventional ICE was invented. In fact, in the 1880s, different inventors demonstrated viable prototypes of both EVs and ICE vehicles in the US and Europe before ICE vehicles became the dominant technology (Høyer 2008). Others focused their attention on the potential for steam-powered vehicles.

As was the case for ICE technology, when first invented, EVs were intended to replace horses as the primary means of vehicle propulsion. Horse-drawn vehicles had been the dominant mode of transportation for goods and people before the 20th century, but these were expensive to maintain and mostly used by the rich (Park City Museum 2007). The limited cost efficiency of moving goods using these means drove the search for a new technology. Charles Steinmetz, a researcher in electricity, noted in 1902 that "(o)ne of the greatest evils in our economic system today is the high cost of distribution, and I am convinced that a greater use of the electric truck will mean a considerable decrease in the cost of distribution especially of food commodities" (The Horseless Age Company 1902).

Thomas Edison saw great promise in EVs, predicting that, "in 15 years, more electricity will be sold for electric vehicles than for light" (Anderson and Anderson 2010). Ultimately, we now know that ICE vehicles became the dominant ground transportation technology for at least the next hundred years, both for passenger and freight movement, in the form of passenger cars and trucks, respectively. Even so, it is worth reviewing their early history before turning to progress made on EVs recently.

At the end of the 19th century, EV development was dominated by private companies, with EVs accounting for around a third of all vehicles on the road (Matulka 2014). Private charging infrastructure, however, did not follow vehicle supply, thus inhibiting EV use (Anderson and Anderson 2010). The lack of charging infrastructure was especially problematic since early EVs had a range of 30 to 40 miles and a top speed of 20 miles per hour, making them largely unsuitable for inter-city travel. Some contemporary commentators therefore argued that EVs would mostly be an urban phenomenon where charging infrastructure would be less of a problem (Høyer 2008). At the same time, the supply of gasoline was becoming more reliable and affordable, thanks in part to new discoveries of gas supply in Texas. Over the course of the next decades, momentum shifted in favor of ICE vehicles, not just because of their availability, but also because of considerable public investment in fossil fuels.

US public sector support for EVs, on the other hand, was delayed several decades until there was rising concern about the pollution impacts of the fossil-fuel powered transportation system. The 1963

Clean Air Act and its amendment, the 1966 Electric Vehicle Development Act, earmarked funding to conduct research on ICE tailpipe pollution. Multiple government entities began conducting research into EVs (Anderson and Anderson 2010). Government support expanded through the 1970s, spurred by the gas shortage. Another clear government response from these crises was the adoption of the Environmental Protection Agency's Corporate Average Fuel Economy (CAFE) standards in 1975 that mandated vehicle manufacturers comply with a minimum fuel economy for the fleet they produced.

Though CAFE standards and other public initiatives were leveraged to encourage higher fuel efficiency among ICE vehicles, in the new millennium, there was a renewed interest in EVs due in part to increased environmental awareness. Anderson and Anderson (2010: 77–8) note that as of 2007, at the federal level, "literally hundreds of bills were introduced to support all types of alternate fuels (…) the legislation was intended to promote use and research through tax credits, guaranteeing loans for research projects, and providing loans and grants for research and development."

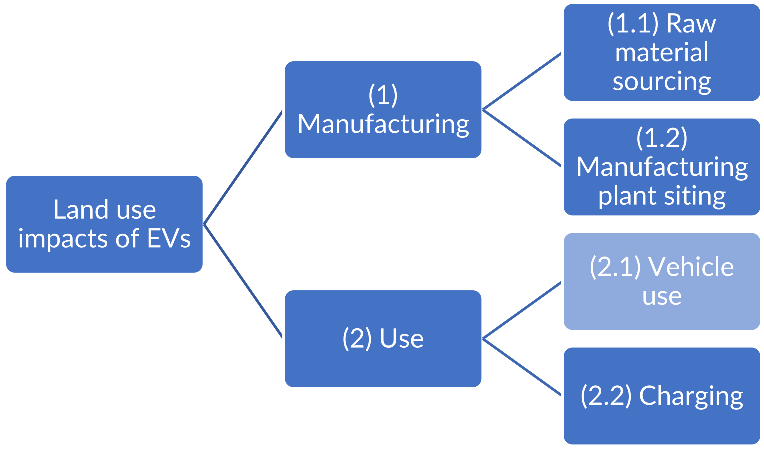
CAFE standards. later rebranded as SAFE (Safer, Affordable Fuel-Efficient) standards, may provide an important tool for the federal government to nudge the market towards EVs. SAFE standards naturally led to a transition towards EVs as more stringent efficiency in terms of energy use per mile driven is demanded from vehicles—physically impossible to achieve with ICE technology.

Other tools that have been more recently used by the government include the introduction of tax credits for EV purchases in the Energy Improvement and Extension Act of 2008, which were expanded by the 2022 Inflation Reduction Act (IRA). The Infrastructure Investment and Jobs Act also provides funding for EV infrastructure and flexible funds that could be used for battery manufacturing, grid updates, retooling auto industry facilities, and retraining and rehiring existing auto workers.[34] These incentives and investments may spur demand for EVs (Jenn, Springel, and Gopal 2018). With certain restrictions on domestic manufacturing implemented in the IRA, the private sector has also increased its investments in local supply chains for both vehicles and batteries.[35]

Land use impacts of EVs

The land-use impacts of EVs can be explained at least in part by categorizing their components (figure B.17). First, EVs impact land use through their manufacturing processes (1), which involve raw material sourcing and manufacturing plant siting. Second, EV use has direct impacts (2), both through vehicle movement and also through the charging processes needed to power the vehicles.

Figure B.17 Land-Use Impacts of Electric Vehicles



In this section, we do not focus on vehicle use since the land-use impacts for this category are little different from those of ICE vehicles. Many of these impacts are discussed in the highway section above. That said, a major potential difference between ICE vehicles and EVs is the potentially lower cost of operating EVs, which could lead to more highway use and thus sprawling development patterns (Orsi 2021). Even so, EVs have land-use impacts related to raw material sourcing, manufacturing plant siting, and vehicle charging.

Raw material sourcing

Steel and aluminium are the predominant raw metals used in the production of EVs, as with ICE vehicles. However, EV batteries have unique material requirements, such as the need for a diversity of minerals like lithium, cobalt, nickel, manganese, and graphite, which are not typically found in conventional ICE vehicles. The expected mass adoption of EVs in the coming years will likely require an expansion in the mining of these minerals.

The mining of minerals needed for EVs is concentrated in certain parts of the world. As an example, most lithium mining is concentrated in the "lithium triangle" of Argentina, Bolivia, and Chile, which collectively contain 67 percent of proven world reserves of this metal.[36] With the IRA's battery material requirements mandating sourcing from the United States or from free-trade agreement countries, the sourcing of minerals is likely to shift for EVs purchased by American consumers.

Any mining can cause environmental harm, but lithium mining specifically is associated with high water consumption, leaching of toxic metals, soil degradation, and air contamination.[37] The mining of cobalt, another element used in EV batteries, can produce toxic by-products that can contaminate groundwater sources and affect nearby communities. Banza et al. (2009), for example, found higher concentrations of cobalt in urine samples from populations living closer to cobalt mines in Katanga, in the Democratic Republic of the Congo, especially in children. Due to the nascent nature of this issue, it is still too early to draw any conclusions and there is a dearth of research on this topic.

Manufacturing plant siting

Batteries are the critical component differentiating EVs and ICE vehicles. Battery manufacturing is currently concentrated in China, Japan, and South Korea. IRA requirements are expected to shift this trend for vehicles sold in the United States as there is a requirement that these batteries be produced in North America.[38] According to White House analyses, in 2022 the private sector announced $13 billion in domestic EV manufacturing. US automobile manufacturing has been concentrated in rural communities, due to labor costs and capacity; taxes;[39] and even culture (Mair, Florida, and Kenney 1988). While the land-use impacts of these locational choices are diverse, researchers analyzing siting in the town of Georgetown, Kentucky found that the decision to locate a manufacturing plant therein indirectly resulted in 8,500 acres of development of previously rural land into industrial, commercial, and office uses and 38,000 acres of residential uses (Ghosh and Chifos 2017).

The location of EV manufacturing facilities—both for the batteries and the vehicles themselves—might follow similar trends. Based on recent experience, continued expansion of EV production facilities would likely mean increased exurban development, automobile dependence of workers themselves, loss of agricultural land, and reduction of wildlife habitats (see "highways" section). Some manufacturers have already started retooling their existing plants as they transition production to EVs, such as through the addition of new metal presses.[40] As more production shifts to EVs, and with IRA requirements for domestic production, others may follow suit.

Charging

The location of EV chargers could play a major role in mediating the impacts of EVs on land use. As noted, the lack of accessible charging in the early 20th century helped tilt the scale towards the mass adoption of ICE vehicles rather than EVs. But the rise of modern EVs offers an opportunity to shape chargers' locations. Charging stations can be located on private or public property, in urban spaces, or along rural roads and highways, depending on their use case.

Scholars focus on creating optimization algorithms and methods to propose charging locations (e.g., Csiszár et al. 2019; Karolemeas et al. 2021; Liu et al. 2018), but little research has been conducted on the impacts of these decisions on land use. Only one study has evaluated the disparate location of EV chargers, showing that historically disadvantaged and impoverished populations in the Chicago region have lower accessibility to EV charging (Carlton and Sultana 2022). In this case, the socio-demographic characteristics of the population living in certain areas led to the disparate location of EV charging infrastructure likely due to the private nature of these companies that prefer siting the infrastructure in wealthier areas, but there was no further analysis to show if this in turn led to land-use changes.

The 2021 Infrastructure Investment and Jobs Act created the National Electric Vehicle Infrastructure (NEVI) formula program that makes $5 billion available to states to deploy charging stations (along with another $2.5 billion available in the Charging and Fueling Infrastructure Grant program). Program guidance requires that stations be located alongside Alternative Fuel Corridors (federally designated highways that prioritize EV charging infrastructure) and requires states to consider the location of existing connections to the electric grid, off-highway travel centers, fuel retailers, and small businesses, while prioritizing underserved and disadvantaged communities. Though funding is now becoming available, multiple states are already conducting analyses on their existing land-use patterns to select potential locations for the deployment of charging stations under NEVI.[41] Although no analysis has been carried out on the land-use impacts of these investments, it can be assumed that charging locations will either be built around existing auxiliary infrastructure such as restaurants and convenience shops as is currently the case with rest locations along highways, or new infrastructure of this type could be built around new EV charging stations. Since depending on the charging speed, charge duration can last between 45 minutes to 12 hours, the types of auxiliary infrastructure could be different to the one that currently exists around gas stations.

The location of urban charging may also have impacts on land use. Chargers require little land area and can be incorporated into existing public infrastructure such as light poles (Kothari and Werthmann 2021), but cars require dedicated parking spaces to charge. The required parking area and long charging duration may lead to conflict over use of limited urban land if cities are to ensure adequate supply of chargers to support growing EV demand. Urban charging infrastructure deployed by individuals has the same issue as public infrastructure as cars will require parking spaces while charging, but this type of infrastructure can also create hazards for pedestrians. Furthermore, municipalities might start mandating a minimum number of EV chargers in new constructions, which will have an impact on housing costs. Colorado, for example, is already considering such a regulation.[42]

An additional consideration for charging infrastructure deployed by individuals is the difficulty in installing infrastructure in multi-family dwellings where tenants might need approval from property managers. This can lead to an unequitable distribution of chargers and difficulty in accessing EVs for people not living in single-family houses; on average, people living in apartments have lower mean incomes than those living in single-family houses (US Census Bureau 2021).

Some estimates indicate that the country would need to generate 20 to 50 percent more electricity if all cars were EVs.[43] While EVs are more energy efficient than ICE vehicles, a cleaner energy source will better support the United States' current goal of reducing emissions by 50 to 52 percent by 2030, especially given the major role of transportation in contributing to greenhouse gas emissions. Orsi (2021: 4) modelled the land required if up to 40 percent of the US car fleet were EVs and found that "the US should devote over 6000 km^2 (roughly the size of Delaware) to solar or almost 70,000 km^2 (more than the area of West Virginia) to wind."

Other impacts of electric vehicle technology

Other than the above land-use impacts, the adoption of EVs could have impacts on employment. Jaeger et al. (2021) conclude that a transition to EVs could result in a net gain in jobs. They note that the manufacturing and maintenance of EVs is less labor intensive than that of a comparable ICE vehicle. On the other hand, battery and charging infrastructure manufacturing could produce a major increase in the number of total jobs. The losses and gains will not necessarily happen in a single country, as manufacturing of these new components, as noted, is distributed around the world.

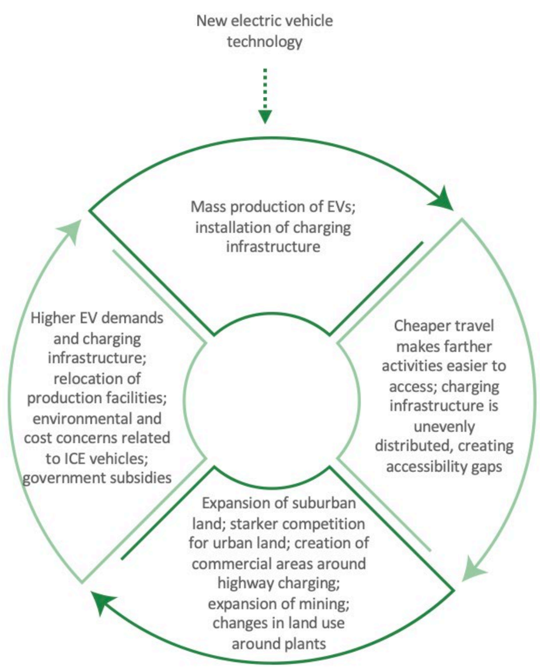
A potential negative impact of EVs is their impact on road safety. Due to their batteries, EVs are heavier than similarly sized ICE vehicles and therefore their impacts in crashes against vulnerable road users or other vehicles will be larger.[44] This has equity implications since Black and Hispanic people are more likely to die from road violence than White or Asian populations (Raifman and Choma 2022). The weight of EVs could also result in faster deterioration to bridges and other infrastructure as well, and many parking garages will need to be reinforced to support the increased weight of EVs.[45]

Some of the most tangible benefits of a transition to EVs are the pollutant reductions that switching from ICE vehicles could entail. Through a meta-analysis of academic publications, Requia et al. (2018) find evidence of a reduction in carbon dioxide emissions and criteria pollutants such as particulate matter (PM) and sulphur oxide (SO2), but the magnitude of the reduction depended on variables such as the source of electricity, the type of EV, and driving and charging patterns, among other characteristics.

The electric vehicle–land use feedback loop

Again, we use Bertolini's (2012) transport-land use feedback cycle to project the relationships between EVs and land use. Figure B.18 illustrates the reinforcing nature of a change in technology from ICE to EVs. We show that as demand and government support for EVs increases, private-sector companies increase production of EVs and the installation of charging infrastructure. This leads to cheaper travel that improves access. Unequal location of charging infrastructure, however, could result in potential benefits not being evenly distributed. With cheaper travel comes the expansion of suburbanized land as people find it easier to travel long distances. Meanwhile, new commercial areas are created along highways to support travellers charging their vehicles during long trips. Similarly, higher demand for charging infrastructure in urban locations creates more competition for scarce urban land. Increased manufacturing leads to the creation or expansion of production facilities, which in turn create land-use changes within their vicinities. Higher demand for batteries leads to the creation of new mines to access the raw materials needed. This creates environmental and equity issues surrounding these locations. This cycle brings us back to increased demand for EVs and government support.

Figure B.18 The Electric Vehicle-Land Use Feedback Loop



While historically, there was little government support for EVs, since the 1970s the federal government has played an increasing role in encouraging the development of this technology. This support has grown with the adoption of consumer purchase incentives in the form of the IRA's reinforced tax credits. The constraints with which EV manufacturers need to comply to ensure their vehicles are eligible for these tax incentives will lead them to make key decisions about manufacturing locations being located within North America, which will have effects on the surrounding land. It is unknown if these changes would have happened without government support, but they are happening now because of that government support.

What would an alternative universe look like?

Government support for EV research began in the 1970s due to air pollution and oil cost concerns, as noted. Today, government support for this technology is being touted to tackle climate change. The Biden Administration has set a target for a 50 percent EV new car sales share by 2030. This likely creates an incentive for it to find ways to support this technology. But what would happen if the federal government did not support EV development while still trying to tackle climate change, improve air quality, and harness escalating oil prices?

As we saw from the collapse of the nascent EV industry in the early decades of the 20th century, the EV industry would likely not have recovered, since it is unclear whether there is adequate latent demand for EVs. Tesla, for example, has received at least $4.9 billion in government support.[46] The federal government is spending another $5 billion on charging infrastructure incentives as part of the NEVI program, and the consumer tax credits for EVs in the IRA will cost at least $7.5 billion.[47] In China—currently the leading consumer of EVs—the government paid more than $29 billion in subsidies to the EV industry in the period between 2009–22.[48]

Solely from a climate perspective, EV subsidies are amongst the most expensive ways to mitigate carbon dioxide emissions among a set of alternatives such as subsidizing solar panels (Gillingham and Stock 2018). This means that government subsidies could be allocated to other solutions solely from a utilitarian perspective, such as investments aimed at reducing motorized travel demand, and this could have had a bigger impact on reducing emissions. Furthermore, as we showed in the feedback loop, the lower operating costs of EVs may exacerbate the perverse land-use patterns that cars and highways have created. Providing more public subsidies may further cement auto-dependency and its externalities.

The Netherlands presents an example of a more balanced approach to public transportation spending rather than EVs. It recently announced a plan to spend 7.5 billion euros in accessible neighborhoods, 1.1 billion euros on cycling infrastructure, and just 2.9 billion euros on the primary road network.[49]

Implications for the AV ecosystem

Like EVs, most AVs will be variations of regular ICE vehicles—whether they carry passengers or freight. Some of the lessons drawn from both ICE and EVs could also apply to AVs. First, AVs have the potential to reduce the cost of driving by converting in-commute "dead" time into productive time. From the EV example we saw that a reduction in cost could lead to increased sprawl. While policies to counter this have not yet been implemented as far as we could identify, ideas such as vehicle miles travelled taxes have been proposed.[50] By charging drivers by the miles they travel, governments could discourage longer trips and therefore reduce the effect that lower vehicle operating costs might have on sprawl. Furthermore, such a policy might discourage empty miles that an autonomous vehicle could drive without a driver (e.g., when parking is unavailable or too expensive).

Linked to this last point, a second lesson to consider for AVs is the availability of urban land for vehicle storage. An AV future could be plagued by driverless vehicles circling around already-busy urban streets while passengers go about their day. A policy question to consider is whether it is the responsibility of the government to accommodate these vehicles as it is currently doing with the deployment of public EV charging infrastructure and adjacent parking. Given the current level of government support for EV charging infrastructure, we can assume that the perceived benefits of EVs outweigh the downsides of dedicating public infrastructure to accommodate EV drivers. Would the same conclusion be reached in an AV future where the public space is given away to private AV owners?

Lastly, will the government use its monetary power to support the industry before it follows the same path as the early EV industry? Given that there are more cost-beneficial alternatives to spending public money on EVs when it comes to climate change, we can assume that policymakers and elected officials are also considering non-climate benefits when choosing to provide support to the EV industry. Among these could be an industrial and jobs policy that would like to see the automotive industry continue to be an economic driver for the country. This duality is exemplified by US Energy Secretary Jennifer Granholm, when noting that "producing advanced batteries and components here at home will accelerate the transition away from fossil fuels to meet the strong demand for electric vehicles, creating good-paying jobs across the country."[51] This phenomenon could be replicated in an AV future where the government could provide direct subsidies to the industry to keep it afloat and able to compete in a globalized economy. A policy question here would be if that is a reasonable and beneficial way to spend public monies, or if there are other better alternatives.

Appendix C: Conduct of research report

Throughout our work, we engaged in continuous dialogue with the NCHRP panel that supervised the work. The panel provided insight into elements of our research that were missing and offered comments on how we could improve our toolbox to ensure it provided the array of outcomes that would best meet the needs of policymakers and other stakeholders.

Conducting the literature review and establishing the state of the practice

We undertook a detailed examination of recent scholarship related to both the AV ecosystem and land-use policy. We focused on finding articles that sought to explore the intersection between these two policy areas by using Google Scholar as well as a review of recent publications by the Transportation Research Board. We also asked members of the NCHRP panel to recommend studies that we might have missed. For each article we identified, we developed an annotated bibliography. We then categorized key findings from the different articles, with the goal of summarizing what current scholarship can tell us about each of those issues.

To conduct our analysis of the state of the practice, we built on work that we had already conducted as part of a separate project to identify how policymakers in the United States and in other parts of the world are thinking about responding to the potential connections between the AV ecosystem and land use (Freemark et al. 2022). We used a database provided by the National Conference of State Legislatures to identify policies related to AVs in general, and then reviewed those to identify any references to issues related to land use. Using news sources, we then identified a select group of local governments that had developed plans related to AVs and that mentioned land use. We used these as case studies in our analysis.

Conducting our review of historical transformative transportation technologies

We worked with the NCHRP panel to identify a list of several examples of historically important and transformative transportation technologies. After consideration of roughly a dozen ideas, we landed on the five case studies that we explore in detail in Appendix B.

For each case study, we conducted a detailed review of available information related to the history of that technology and its association with land use outcomes. We looked for references that mentioned how public policies had played a role in the technology's rollout and the ways in which those policies may have mediated the intersection between the technology and land uses.

Developing the community typology

We developed the typology based on a review of scholarship related to what key community characteristics would be influenced by the rollout of the AV ecosystem, and which could most influence that rollout. The key characteristics that we identified included:

- **Density, meaning the concentration of people and employment over land area.** Scholars estimate vastly divergent potential land-use effects of AV deployment based on concentration of land use (Wu, Cao, and Douma 2021). For example, while many researchers predict that AVs could allow for the redevelopment of parking lots for new residential or commercial use, they also emphasize that that this sort of redevelopment is only likely in communities of a minimum density (Stein 2020). Density, for example, may also predict what types of impact AVs have on residential sorting; in some cases, denser areas may lose population (and less dense areas may gain it) if the vehicles ease commuting. This may encourage further sprawl similar to that following investments in the Interstate highway system over the course of the mid 20th century. This movement of people could affect what types of policy tools state and local leaders could use in response to—or to prevent—suburbanization. On the other hand, denser communities may also be more likely to accommodate further population growth if AVs reduce traffic, provide safer streets, and allow for redevelopment of underused parking lots.

- **Population change or development pressure, meaning a community's economic and social trajectory related to land costs and/or influxes or declines of people, jobs, and real-estate investments.** Scholars have shown that logistics centers, for example, are likely to be situated at the edge of rapidly developing metropolitan areas (Sciara, Lovejoy, and Handy 2018). These centers are likely to play a major role in a future autonomous trucking industry. But they are less likely to be located in regions experiencing limited growth, since they need a strong local market to which to distribute goods.

- **Car and truck reliance, meaning the dependence of a community on privately owned passenger vehicles on the roadway network to provide residents access to essential needs, and on large trucks—rather than trains and cargo bikes—to move goods from one place to another.** For example, scholars emphasize that certain forms of AVs, like autonomous buses or pooled ride-hailed AVs, are more likely to be used in communities where people are less likely to need to drive to get around (Wu, Cao, and Douma 2021). The use of these shared-passenger services could affect the possibility of creating dense town centers with high concentrations of residents and jobs, which could improve both equity and sustainability.

Given the three major community characteristics we identified, we then further classified them into what we refer to as the three **typological elements** that define how communities may be influenced by—and may influence—the AV ecosystem rollout:

- For **density**, we classify communities as:
    - High density (e.g., urban centers)
    - Moderate density (e.g., many suburban areas)
    - Low density (e.g., exurban and rural areas)
- For **population change or development pressure**, the main characteristic that we believe would influence policymaking at the intersection of the AV ecosystem and land use is whether the community is experiencing rapid population and employment growth and therefore significant pressure to develop real estate, both for residential and employment uses. In some cases, communities are not experiencing rapid growth (e.g., because of exclusionary land-use regulations), but they nonetheless have significant development pressure due to the desire of people to live within them (this could occur in a gentrifying neighborhood, for example). We therefore divide communities into:
    - High pressure
    - Low pressure
- For **car and truck reliance**, the key question is whether a significant share of the population can meet their daily transportation needs without using a private car, and whether most goods must be shipped by truck, or whether other options, like freight rail or cargo bike, are feasible. We therefore separate communities into:
    - High or moderate car and truck reliance

- Low car and truck reliance

For each of these typological elements, we provide details about how they can be calculated using a series of publicly available data in the fact sheets that follow. Communities should assess the degree to which their characteristics fit within each of these elements.

Community typologies

We do not classify all US states or localities into this typology; doing so would be beyond the scope of this project given the massive number of such entities and the reality that individuals on the ground may have different views about the circumstances they find themselves in and what data are able to tell us. Moreover, we believe that the concept of "community"—the desired environment in which planning for the AV ecosystem and associated land uses—may extend beyond the set boundaries of states or municipalities. Indeed, policymakers may want to consider how to conduct such planning at the neighborhood, county, metropolitan, or some other scale, all of which might meet the definition of "community," depending on the context. These are possibilities we enable through the design of the toolbox.

As such, we plan to allow toolbox users to self-identify what "type" of "community" for which they are planning. In our final toolbox, we plan to incorporate a self-assessment to allow users to select into a community type. The toolbox will then allow them to understand how the aspects of their community correspond to potential AV–land use interactions and also potential policies that can help them advance the goals of equity and sustainability.

In this section, we describe our approach to developing this community typology and provide a description of the 12 community types that fit into this typology. We developed these types based on our reading of the existing scholarship on expected interactions between AV and land use—as well as our findings from our previous exploration of historical precedents. We also offer a list of example data sources users may be able to leverage as they are working through the "quizzes" (we will expand on this list in more detail in the indicators and metrics phase of the research we plan in the coming months). We then offer evidence for how we expect the AV–land use interaction to occur based on evidence from past research.

Developing the typology

We base our typology on the following premises. First, we assume that a community's characteristics (e.g., its density or its population) will influence the ways that the AV ecosystem and land uses interact. Second, we assume that those characteristics will also influence which policymaking tools will be most effective there—and, indeed, which particular design or version of such a tool will best further policymakers' goals in advancing equity and sustainability. We conducted a series of brainstorming sessions as a joint project team to explore how to concretize these insights for the toolbox. We also chose to assemble our advisory stakeholder group to receive further outside perspective about how to proceed with our approach. We collected insight from five members of that group during a video call that we held.

Following this consultation process, we agreed that the ways in which policymakers may harness tools to impact the AV–land use interaction (and, indeed, whether they should harness those tools at all) vary based on community characteristics. For example, a city's current spatial form (e.g., whether it is largely composed of undeveloped greenfields or densely developed parcels) may be most relevant to zoning policies; and local real-estate demand levels may be important for identifying potential development sites (e.g., whether surface parking lots are redeveloped). Moreover, the ways that an AV is rolled out is likely to reflect community characteristics. For example, AVs may be more likely to be leveraged for shared ride-hailing in denser neighborhoods.

As we developed this approach, we agreed that the characteristics that predispose a community to earlier or more extensive AV adoption are not necessarily the same characteristics that would inform policymaking related to AV interaction with land uses. In other words, it is possible that the AV ecosystem is more likely to be quickly deployed in communities in California's Bay Area because of the presence of large tech companies there, but that being in the Bay Area in and of itself may not be a defining factor in determining what strategies policymakers should pursue. Our presumption for this work is that the AV ecosystem is something that will be deployed nationwide, and thus that policymakers in every sort of community throughout the United States should be considering how to plan for its introduction, no matter how quick or slow that introduction may be.

To develop the community typology we first worked as a team to list general types of tools that—after our reexamination of the literature review and historical examples analysis from previous phases of this research project—we determined would likely be included in the toolbox. These included:

- **Tools that primarily impact the built environment (e.g., zoning and building codes);**
- **Tools applied at the vehicle scale (e.g., operational regulations); and**
- **Fiscal or economic tools (e.g., mileage-based fees and rules governing transportation investments).**

Through our brainstorming sessions, plus consideration of our literature review and historical examples, we narrowed this list to tools that are most often within the remit of state and local governments and those that could have a mid-level or high influence on the relationships between the AV ecosystem and land uses.

In our review, we identified a community's fiscal capacity as an enabler of, or constraint preventing the implementation of, several of the tools we expect to include in the final toolbox. As such, we also considered including it in the typology. High fiscal capacity, however, does not necessarily mean that planning for the AV–land use nexus would be a budgetary priority.

Based on our review of the scholarship and previous historical examples, we also identified several key related community characteristics that are likely to have a smaller impact on the AV–land use relationship, but which remain important to consider for local policymakers. These include:

- **A community's demographics.** Communities with a higher population of children, older adults people, or people with disabilities may be more likely to adopt AVs for passenger use due to those individuals currently being excluded from the human-driven transportation system. Even so, we did not find evidence that these demographic differences are likely to significantly impact broader land-use issues.
- **A community's geographic environment.** Communities located in places with few opportunities for development (e.g., because they are located along a coastline) may adapt to AVs in a manner that focuses on their potential to build up, rather than out. This could have significant impacts on land use but is likely to be extremely varying from community to community and thus difficult to summarize for a national audience.
- **A community's resident incomes.** Communities with higher resident incomes may be more likely, for example, to attract a higher level of freight-based automated service, from the pure perspective of their having higher buying power and thus may attract more home deliveries, especially of more expensive goods. Even so, we believe this element is largely captured in the population

change/development pressure measure, which is more important from the perspective of future land-use changes.

- **A community's political environment.** Different communities may be more or less apt to have local officials who are interested in planning for the AV ecosystem, such as whether they are interested in shifting away from private-car based transportation—or encouraging infill development. They may also choose to emphasize some policymaking approaches over others. These variations could play a major role in influencing land-use outcomes, but identifying these political differences is outside of the scope of this project.

Review processes: Engagement with an external stakeholder group

To inform this toolbox and ensure that it meets its goal, we formed an external stakeholder group to review drafts and discuss issues with us over the course of the project research period. This group included land and transportation planning professionals; state, local, or municipal government land use and transportation planners; private AV technology developers and implementation companies; community organization leaders focused on technology and sustainability in urban planning; disability advocates with a specialty in transportation; and urban development and sustainability nongovernmental organizations.

We conducted initial interviews with stakeholders to understand their knowledge and interest in the development of a toolbox for future policy development and implementation of AV technology. Stakeholders were informed of their commitment to the group and what information they would be asked to provide. A kickoff meeting was held February 2023 to share the goals of the work, process, timeline, and expectations from the group. In addition, in order to inform the research and development team's efforts, we asked stakeholders about their immediate concerns related to AV technology and its relationship to land use; what current policies and guidelines they were aware of that the research team should also be aware of; how they would like to see the project moved forward; and other considerations that should be made for the development of the toolbox. Their feedback included consideration of implementation and impact of AV technology on different scales and densities of land development; the intersections of land use, accessibility, mobility, and inclusion, environmental sustainability; and long-range land use and AV technology visioning.

These initial insights from the stakeholder group informed our planning for the toolbox. In Table C.1, we list the stakeholder group members.

Table C.1: List of Stakeholder Group Members

Stakeholders	Organization
Ashley Hand	Kansas City
Becky Steckler	ECO Northwest
Bill Pugh	Coalition for Smart Growth
Darnell Grisby	Beneficial State Foundation
Giancarlo Valdetaro/Corrigan Salerno	Transportation for America
Jennifer Henaghan	Green Communities Center
Joe Shannon	Motional
Karina Ricks	Cityfi
Kelley Coyner	Mobility e3
Kevin Lacy	State of North Carolina

Maria Town/Kristen Cox	American Association of People with Disabilities
Marisa Rodriguez-McGill	Lyft
Michael Burton	Fairfax County, Virginia
Patrick Smith/ Seth Contreras	New York City DOT
Quincy Brown	We All Rise
Sahar Shirazi	Nelson Nygaard
Veronica Davis	City of Houston

In parallel with the completion of the literature review, in December 2023 through January 2024, the project team reconvened the stakeholder group in small group check-in meetings and a large group meeting to brainstorm policies, indicators, and metrics that would help implement and measure the equity and sustainability of AVs in relation to land use. We specifically askedhow they might inform the development of the toolbox and audiences that should be considered.

Many of the considerations that emerged from the kickoff stakeholder meeting came up again as stakeholders mentioned the importance of contributors from different levels of community, private developers (land and technology), and government having a role in the implementation and maintenance of systems or programs, as well as the scale to which technology was implemented and its impacts on current systems.

Several stakeholders recommended that the toolbox should mention how policies would most likely have to change—instead of having AV technology fit the policies and systems currently in place. Stakeholders recommended indicators and metrics including transportation efficiency, reduced VMT, pedestrian and vehicle safety, climate emissions, affordability for people with lower incomes, economic impacts like job creation, and overall community improvement.

As for creating policy and tools that could help with sustainability and equity, stakeholders contributed that concrete goals and definitions of what these concepts look like should be clearly stated in the toolbox and there should be obvious integration and applicability of disability considerations in the implementation of AV technology. They also noted that there are plenty of past technology implementations on land use that can inform the toolbox and policy makers on how to avoid inequity and unsustainability on the future of AV technology.

Our last engagement with the stakeholder group was in April and May 2024. This focused on getting feedback on the draft toolbox. Additional individuals (see Table C.2) who had not been part of the initial stakeholder group were brought into the process to ensure that we received feedback from individuals who had not been involved in the development of the product and were seeing it for the first time. The group was provided with a copy of the draft toolbox, a link to a survey, and notes pages with instructions to review the toolbox and share insights via a survey and notes page. We asked the group to focus, in particular, on the topics, layout, ease of use, and general accessibility of the toolbox. Nine stakeholders provided reviews and extensive comments after reviewing the toolbox.

Table C.2. Individuals outside of the stakeholder group who shared their experience of reviewing the toolbox

Individual	**Organization**
Robin Chase	Founder, Zipcar
Ben Holland	Rocky Mountain Institute
Katie Economou	Association of Metropolitan Planning Organizations

The insights from the survey provided helpful feedback around initial thoughts, how to navigate the toolbox, sections they found most useful, sections that required some additional attention, and usability of the toolbox. Stakeholders had varying views about the toolbox. In final revisions of the toolbox, we endeavored to respond to their concerns and ensure a final product that meets the needs of the greatest variety of stakeholders possible.

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