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Autonomous Vehicles, Mobility, and Employment Policy: The Roads Ahead

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Executive Summary

Fully autonomous cars, trucks, and buses, able to operate across wide geographical areas with no drivers necessary, would revolutionize ground transportation. The number of accidents and fatalities could drop significantly. Time that people waste stuck in traffic could be recovered for work or leisure. Urban landscapes would change, requiring less parking and improving safety and efficiency for all. New models for the distribution of goods and services—the “physical internet”—would emerge as robotic vehicles move people and objects effortlessly through the world, on demand.

We might also see human drivers, relieved of the attention burdens of driving, liberated to clog the streets and pollute the air with many more miles traveled. We might face cities congested with autonomous delivery robots. People might abandon public transit for comfortable autonomous bubbles, leading to a collapse of public infrastructure. Millions of Americans who earn a living making, driving, and supporting automobiles could be out of work.

Automated driving technologies have promised to disrupt urban mobility for a long time. Especially since companies began announcing major breakthroughs after 2010, automated driving technologies have begun to raise fears of mass unemployment in transit systems and mobility-related industries like trucking. This research brief considers the current state of automated driving technologies, including

driver assistance systems and highly automated vehicles (AVs), as well as their potential implications for mobility and employment. Broader impacts, including the interplay with transit and land-use and environmental consequences are also briefly considered.

Visions of automation in mobility will not be fully realized in the next few years, as recent developments indicate that a major transition will not occur suddenly. Rather, analysis of the best available data suggests that the reshaping of mobility around automation will take more than a decade. We expect that fully automated driving will be restricted to limited geographic regions and climates for at least the next decade, and that increasingly automated mobility systems will thrive in subsequent decades. Still, even gradual increases in automation will have profound impacts on the movement of people and goods throughout the world. Moreover, automation in cars will not occur in isolation, but within a web of relationships with electrification, connected vehicles, and evolving service models across vehicle types.

This extended lead time means that policymakers can act now to prepare for and minimize disruptions to the millions of jobs in ground transportation and related industries that are likely to come, while also fostering greater economic opportunity and mitigating environmental impacts by building accessible mobility systems.

The adverse employment impacts from the COVID-19 pandemic add greater urgency to this topic. COVID-19 has exacerbated the existing inequities in mobility and employment in cities and has dealt a blow to public transit systems and ridesharing. The surge in e-commerce has increased interest in robotic package delivery, and more workers are currently working from home. As commuting, education, and shopping patterns move toward a new normal, safe and efficient public transit will remain vital for our cities. Investments in workforce training are needed now more than ever to ensure that workers impacted by COVID-19 have a place in the automated mobility systems of the future, however long that future takes to arrive.

KEY FINDINGS:

- The widespread deployment of fully automated driving systems that have no safety driver onboard will take at least a decade. Winter climates and rural areas will experience still longer transitions.
- Expansion will likely be gradual and will happen region-by-region in specific categories of transportation, resulting in wide variations in availability across the country.
- The AV transition will not be jobless. New opportunities will arise for employment, such as in the remote management of vehicles, but the quality of these jobs is uncertain, and depends somewhat on policy choices.
- AV should be thought of as one element in a mobility mix, and as a potential feeder for public transit rather than a replacement for it. However, unintended consequences such as increased congestion remain risks.

- AV operations will benefit from improvements to infrastructure, which can create positive spillover effects with respect to jobs, accessibility, and the environment. This includes not only traditional transportation infrastructure such as roads and bridges, but also information infrastructure such as communications systems, databases, and standards.

POLICY RECOMMENDATIONS:

- Investing in local and national infrastructure and public-private partnerships will ease the integration of automated systems into urban mobility systems.
- Sustained investments in workforce training for advanced mobility will help drivers and other mobility workers transition into new careers that support mobility systems and technologies. These areas include software, robotics, testing, electrification, vehicle-to-infrastructure communications, and human-machine interaction.
- Dramatic improvements in mobility safety and access should be pursued, with the aim of reducing traffic fatalities and injuries by several orders of magnitude in the coming decades, while also ensuring access for elderly and disabled passengers.
- Increased federal investment in basic research in the technologies that underpin automated mobility will enhance U.S. competitiveness; these include human-machine interaction, robust perception, prediction and planning, and artificial intelligence.

Several key questions remain, which are addressed in this report but as yet not fully answered:

- What is the likely timeline? When will autonomous vehicle systems increase their area of operation beyond today's limited local deployments?
- When will the industry achieve dramatic improvements in safety?
- What are the likely impacts to mobility jobs, including transit, vehicle sales, vehicle maintenance, delivery, and other related industries? In the long run, will automated mobility provide sufficient new jobs and careers to overcome losses in traditional driving-related occupations?
- When will fully autonomous mobility become profitable, and how will this vary across different regions?
- As we recover from the COVID-19 crisis, will the trend toward increased automation in mobility accelerate, or will we see a shift away from shared mobility?
- How should public transit adapt to automated mobility?
- How should we prepare policy in the three key areas of infrastructure, jobs, and innovation?

Introduction

Early rhetoric surrounding self-driving cars set enormously high expectations. In 2011, Google X founder Sebastian Thrun wrote that Google's early self-driving prototypes "drive anywhere a car can legally drive."[1] In 2012, Google released a video in which Steve Mahan, a visually impaired Californian, rode in the driver's seat on an everyday journey through part of the San Francisco Bay Area, going through the drive-thru at a Taco Bell and picking up his dry cleaning; at the close of the video, Steve Mahan was designated as "Self-Driving Car User #0000000001."[2] Later that year, at the signing of a California driverless car bill into law, Google founder Sergey Brin stated, "You can count on one hand the number of years until people, ordinary people, can experience this."[3] The 21st-century space race in technology had begun.[4]

Investments poured into self-driving startups, as automakers and Tier 1 suppliers mobilized large efforts to fend off Google and other potential disruptors. Israeli computer vision startup Mobileye had a highly successful initial public offering in July 2014 that valued the company at $5.31 billion.[5] Thirty-two months later, Intel acquired Mobileye for $15.3 billion.[6] In 2015, Elon Musk predicted that Tesla drivers would soon be able to safely go to sleep in their self-driving Teslas and wake up at their destinations.[7] "In the past five years," Alex Davies wrote in *Wired* in 2018, "autonomous driving has gone from 'maybe possible' to 'definitely possible' to 'inevitable' to 'How did anyone ever think this wasn't inevitable?'"[8]

Not everyone has agreed that a steering wheel free future was inescapable. Self-driving critics such as Steven Shladover of UC Berkeley pointed out challenges that continue to stymie researchers, such as coping with snow and ice and recognizing traffic cops and crossing guards.[9] Robotics researchers, including Mary (Missy) Cummings from Duke University[10] and Gill Pratt from Toyota Research Institute[11], pointed to the dangers that can occur when humans operate highly automated vehicles—such as failing to pay attention when intervention is necessary. Roboticists such as MIT's Rodney Brooks pointed out that recent advances in detecting objects in images does not imply that general-purpose artificial intelligence is close at hand.[12] Co-author David A. Mindell wrote in 2015 that an immediate leap to full autonomy was a less meaningful problem than solving for ideal mixes of human and machine.[13]

Companies such as Waymo, Cruise, Zoox, and others make autonomous driving look easy.[14] There are secrets, however, under the hood of self-driving that make this technology difficult to generalize and make commonplace. Transferring a capability such as recognizing objects in the roadway to a different task, such as interpreting a hand wave from another driver in traffic, remains an extremely hard problem. Conquering autonomous driving in a given geographic area is an important step, but generalization to make the same capability more geographically widespread is difficult. Waymo, which was previously the Google Self-Driving Car project, has recently demonstrated fully driverless capabilities over a large area in Chandler, Arizona. However, this notable achievement may take quite a long time to generalize to other regions that do not enjoy Arizona's sunny, dry climate. The key question is not just "when" but "where" will the technology be available and profitable?

In this research brief, we focus on automated driving for the public roadways, including trucks and light-duty vehicles.[15] We place particular emphasis on what the various technological options mean for impacts and policies, complexity often missed by reports that lump vehicle automation strategies together as one "technology."

The following analysis draws on the authors' research and experience in the engineering, social, and policy dimensions of automation and autonomy in extreme environments of the deep ocean and aerospace, as well as years of engagement with the auto industry, transit, and AV systems.[16] The analysis also draws from published predictions and industry reports, including a series of studies performed between 2013 and 2019 by Morgan Stanley, Deloitte, KPMG, McKinsey & Company, PwC, Frost & Sullivan, and RAND. We incorporate published academic and industry research into AV systems, including simulation studies, white papers, and policy-related work on vehicle automation. We reference social science research that addresses some of the reasons for the cultural success of the personal car in the United States, as well as forthcoming work on the social challenges of AV engineering. Our analysis draws on news articles about AV projects, progress, and automakers' predictions.

The brief also incorporates government and consulting studies on EV systems, especially for consideration of likely environmental impacts, including reports by Argonne National Labs, RAND, the National Renewable Energy Laboratory, the European Commission's Joint Research Centre, the U.S. Department of Energy, the Natural Resources Defense Council, as well as the Center for Automotive Research in Michigan.[17]

A major concern from a policy perspective is jobs, millions of which are susceptible to potential disruption as the task of driving becomes more automated. For example, in 2018 U.S. job totals for selected driving-related occupational categories included: Taxi Driver, Ride-Hailing Driver, or Chauffeur: 370,400 jobs; Bus Drivers: 681,400 jobs; Heavy and Tractor-Trailer Truck Drivers: 1,958,800 jobs; Delivery Truck Drivers and Driver/Sales Workers: 1,449,100 jobs; Automotive Service Technicians and Mechanics: 770,100 jobs; and Automotive Body and Glass Repairers: 177,100 jobs, yielding a total of 5,406,900 jobs for just these six categories.[18]

A rapid replacement of a significant portion of these jobs would present an employment crisis. Employment impacts, however, will depend on the rate of advancement of the technology and the pace of geographical rollout. We believe that these will be slower than many have predicted, which will provide more time to prepare for workforce changes and to study potential impacts on transit and congestion, whose effects might in fact outweigh direct impacts on driving-related occupations.

Automation in driving: a primer

Before introducing the technical outline of self-driving in more detail, we first review the terminology used in the industry to describe the different types of driving automation. No single "self-driving car" technology exists; it is an assemblage of techniques, systems, and service models, the permutations of which have implications for adoption and employment.

LEVELS OF AUTOMATION: STANDARD TERMINOLOGY

The Society of Automotive Engineers defines six levels of autonomy in driving:[19]

- Level 0 systems are fully manual vehicles.

- Level 1 systems provide steering or brake/acceleration support to the driver, but require the driver to be fully engaged at all times. Adaptive cruise control is a common example of Level 1 automation.
- Level 2 systems automate some steering and brake/acceleration tasks, and require that the driver constantly monitors the environment around the vehicle and is ready to immediately intervene when necessary. Level 2 is widely deployed across automakers in 2020, in the form of active safety features, such as automatic lane-keeping combined with adaptive cruise control. Tesla drivers have driven over 3 billion miles using its Autopilot Level 2 automated driving system.[20]
- Level 3 systems can operate without active engagement by the driver for certain geographic settings, so long as the driver is ready to intervene when requested.
- Level 4 systems can operate entirely without a human driver to monitor, albeit within a restricted geographic region, for instance, on a set of predetermined streets in part of a city.[21]
- Level 5 systems relax the domain restriction of Level 4 and could operate anywhere a human driver can—even with no one in the vehicle.

These levels have some internal contradictions and do not capture the full complexity of how automation is likely to evolve in mobility[22], but they have become standard nomenclature in the industry.

HOW DO SELF-DRIVING CARS WORK?

The unseen "magic" behind the scenes of self-driving vehicles arises from the core component technologies of perception, localization, mapping, prediction, decision-making, path-planning and control, and human-computer interaction.[23] Not by coincidence, these are also the core technologies of robotics: Driverless cars are essentially mobile robots. As such, they draw on similar fundamentals as do aerial drones, industrial robots, and other forms of automation. These arenas have seen major technical progress in the past decade, but considerable challenges remain.

Perception systems enable a robot to know what is where in the environment—detecting and tracking other vehicles, bicyclists, pedestrians, traffic signals, and obstacles in the scene. Localization refers to "Where am I?," the ability of the robot to know its position relative to a desired frame of reference. Mapping occurs offline, in advance of operating a vehicle autonomously, and entails the creation of highly detailed models of the world that aid in localization, prediction, and route planning. Many state-of-the-art autonomous driving systems rely on high-definition maps that enable the robot to compute its position with high precision, down to a few centimeters of accuracy.[24]

Prediction adds a time element to perception—where will the things that move in the world go in the future? For example, will the vehicle ahead of the robot change lanes, or will a pedestrian enter a crosswalk? Perception and prediction populate a local-scene model that guides algorithms for behavioral decision-making and path selection. Prediction and planning need to take into account the reactions of other agents to the vehicle's actions, which makes the problem quite difficult. The output of the planner is fed into a low-level dynamic control system that generates steering and accelerator/brake commands to follow the chosen trajectory as closely as possible, while ensuring a smooth and comfortable ride. All these subsystems must be able to respond in real time to changes in the environment, to mechanical and systems failures, and to software and data errors.

Perception is based on inputs from myriad sensors, typically cameras, radar, and lidar (for "light detection and ranging"). Machine learning algorithms play a vital role in processing camera and lidar data. While initial systems relied heavily on lidar[25], technologists such as Elon Musk, Amnon Shashua, and George Hotz have championed computer vision for autonomous driving. Recent years have seen remarkable progress in computer vision,[26] but engineers are still debating whether lidar is necessary, or if cameras plus radar can achieve full autonomy.[27] Computer vision challenges include handling direct sunlight and dealing with the domain adaptation problem, which occurs when a machine learning system is trained with data that is dramatically different from the environment in which a system is deployed.[28] Obtaining high-resolution images at night can also be difficult. Lidar provides direct measurements of range, regardless of lighting conditions; however, lidar sensors can be expensive. Automotive radar is highly affordable, but radar has low wavelength and low spatial resolution.

High definition maps provide a detailed model of the world that enables the robot to predict what sensor data it should receive at different locations in the environment, incorporating models of how its sensors operate. Making these highly detailed maps is costly and time-consuming, as is keeping them constantly updated as the world changes. When a robot's predictions of the world differ slightly from the robot's sensor observations, the difference computed between the predictions and observations can correct the robot's position estimate. However, if the a priori map is inaccurate, the system (or its human operator, if one is onboard) must detect this quickly to take over control. Without accurate high-definition maps, the current state-of-the-art in robotic localization, perception, and decision-making cannot yet enable a robotic vehicle to be turned loose in an unmapped environment without human supervision.[29]

RECENT TECHNOLOGICAL PROGRESS AND OPEN CHALLENGES

Level 2 products like the Tesla Autopilot have shown that in favorable conditions, much of driving can be highly automated, especially on highways and in good weather. In other settings, however, such as congested city streets, unusual highway situations, and inclement weather, the open technical challenges are considerable. While Tesla Autopilot does not rely on a high-definition map, it does require constant human supervision (i.e., someone still at the wheel), even in Tesla's "Full Self-Driving" mode.[30] At present, the online manual for Tesla Autopilot states: "The currently enabled features require active driver supervision and do not make the vehicle autonomous. ... While using Autopilot, it is your responsibility to stay alert, keep your hands on the steering wheel at all times and maintain control of your car. ... It does not turn a Tesla into a self-driving car nor does it make a car autonomous."

Waymo famously pivoted its strategy away from Level 2 to Level 4 after it found that human drivers had difficulties paying attention when monitoring its 2013 self-driving prototype on extended journeys in the

San Francisco Bay Area.[31] One driver fell asleep for 27 minutes, alone in the vehicle, while traveling at 60 miles per hour on California Highway 101.[32] Waymo did not attempt to develop novel interfaces that would keep drivers as glued to their dashboard as they are to their mobile phones.[33]

Level 3 automation is controversial due to the difficulty of ensuring that there is sufficient time to warn drivers of the need to take over when faced with an impending hazard.[34] Since a human driver is still needed to be present onboard the vehicle, however, the impacts of Level 3 are similar to Level 2 for the purposes of this report. Several companies have set targets to provide Level 3 systems that would allow car and truck drivers to perform tasks other than driving, at least at low speeds, such as when driving in traffic jams on a highway. At higher speeds, however, available sensors do not provide a long enough sensing range to be able to hand off control to the driver with ample warning.

Because Level 2 and Level 3 systems still demand a role for the driver, improved driver education about new active safety features is imperative for safe adoption.[35] Humans suffer “vigilance decrement”[36] (where their attentiveness can decrease over time); therefore, even with improved driver education, until more compelling interfaces are developed, driver monitoring systems like those that use computer vision to track the gaze of the driver are highly recommended.[37] Cadillac’s Super Cruise illustrates the successful use of a driver monitoring system in a Level 2 system design.[38]

While Level 4 self-driving has not lived up to its initial aspirations,[39] the technical progress achieved by Waymo and other leading companies in the past few years has been substantial. In early 2020, Waymo “was facilitating 1,000–2,000 ride-hailing trips in Arizona a week, 5 to 10 percent of which were without human backup drivers”[40] onboard the vehicle. Other leading self-driving startups, such as Cruise, Zoox, Aurora Innovation, Argo AI, Aptiv, and Mobileye, have also demonstrated impressive self-driving capabilities in challenging city environments such as San Francisco, Pittsburgh, Las Vegas, and Jerusalem.

Despite this substantial progress, considerable technological challenges remain before we will see the disruptive rollout of fully automated Level 4 driving across wide geographical regions. Removing onboard vehicle operators from large vehicle fleets poses tremendous technical difficulties, especially when considered at scale in a wide diversity of operational domains. Today, even the most optimistic timelines put widespread Level 4 over a decade away.[41] Most predictions agree Level 5 is even farther off than that (beyond 2040, or even entirely impossible).[42] Therefore, this report focuses on the impacts of Level 2 and Level 3 driver assistance and Level 4 automated driving systems.

Automated vehicles in the mobility landscape

Levels of automation provide some useful structure in considering the evolution and impact of automated vehicles. Still, the six levels spelled out by the Society of Automotive Engineers are not by themselves sufficient to consider employment impacts. The fact that these levels are agnostic to the domains in which automation systems operate would change the kinds of services that automated systems can provide.[43] Moreover, as with all technologies, automated vehicles will find their applications as tools used by humans and machines—the deeper the connection is between the technology and existing social environments, the greater the value of the technology. Automation will develop alongside improved infrastructure, profound evolutions of electric and connected vehicles, and evolving mobility ecosystems where new services complement the traditional consumer purchases of cars. These facts are distinct but interconnected, and together will shape the landscape of changes to mobility mix and mobility jobs.

The public language of automated-driving researchers emphasizes “autonomy,” which has traditionally been defined as operating independently of infrastructure. But ironically, today’s driverless cars depend heavily on infrastructure—whether following lines on the road, drawing data from databases and satellites, or relying on charging and fueling stations. For example, Level 4 systems typically depend on high-definition maps, GPS connections, clearly painted lines, minimal potholes, and some level of remote monitoring of the vehicle’s health. Future vehicles may rely on edge computing, navigation augmentation for areas with poor GPS reception, and high-speed 5G networks.

Vehicle automation does not require electrification, but electric vehicles (EVs) have strong synergies with automation.[44] They already have a robust electrical system to support sensing and processing, and promise less maintenance and longer operational life over which to amortize costs.[45] Automation might also make EVs more attractive, by helping to address common consumer concerns about current EVs, such as charging time.[46]

AVs may also support or accelerate the existing evolution toward novel mobility services. Transportation network companies like Lyft and Uber have invested heavily in AVs and are key potential users, with implications for ridership and ride-hailing drivers, as the number of mobility service vehicles is predicted to increase roughly sevenfold from 2015 to 2035.[47] Vehicle sharing is also key for economic feasibility of AVs, given the large up-front costs of sensors and equipment necessary for Level 4 systems[48]. Alternative options for the ways that Level 4 technology might be used to provide mobility services include larger bus or shuttle vehicles with fixed routes, as in the mass transit model. Further study is needed to explore the tradeoffs between fixed and variable costs, vehicle occupancy, frequency of service (known as “headway” in the transit domain), and congestion impacts.

Automated driving does not necessarily require that vehicles connect to smart infrastructure or other vehicles. A consistent connection to other vehicles or remote servers is not a requirement for most systems, which are typically designed to have all required processing and data onboard the vehicle. But connectivity can reduce sensor costs via data sharing, integrate with traffic management to improve flow, and allow greater potential for off-board processing and remote management, as well as providing system robustness through redundancy. Some safety-critical systems, however, will need to remain on-board.

We are likely to see layered systems, with varying degrees of connection to the broader world enabling varying degrees of capability and robustness, depending on geographical area, weather conditions, and other factors.

Cost challenges

Pilotless aircraft such as military drones took more than seven decades to find niche applications, in part because they always had to compete with human-piloted aircraft that benefitted from the same technological advances. Similarly, automated driving will need to become economically viable in competition with human drivers and augmenting technologies such as active safety systems. They will still face cost challenges for sensors, vehicle systems, and infrastructure. These costs, though decreasing, are still high; moreover, research papers that model the market uptake of AV technology sometimes underestimate current costs for high levels of automation by almost an order of magnitude.[49]

The cost of Level 2 systems has dropped precipitously in the past few years, with suppliers such as ZF promising Level 2 systems with automated lane keeping, adaptive cruise control, emergency braking, and driver-initiated automated lane changing for less than $1,000.[50] GM has plans to offer its Super Cruise system on 22 models by 2023.[51] The hardware costs of Level 4 vehicles are not anticipated to drop so quickly due to the much greater complexity of typical Level 4 sensors and computers, combined with the fact that many fewer Level 4 vehicles are in production.

In addition, even absent high capital costs for AV hardware, recent research by Nunes and Hernandez raises concerns for the profitability of projected AV business models. In a case study of a projected AV deployment in San Francisco, they found that automated taxis would struggle to be cost competitive with personal vehicle ownership due to the costs of safety oversight by remote operators, licensing, insurance, maintenance, and other system costs.[52] More analysis of this type is warranted for other locations and types of deployments.

The provision of remote human supervisors to monitor AV operations will also be a non-negligible cost; this is particularly relevant for projections of the cost-per-mile of shared mobility services.[53] It is unclear how many autonomous vehicles can be remotely monitored at once with proposed remote driving/monitoring approaches.[54]

Furthermore, costs of roadway infrastructure modernization do not factor into most projections of AV proliferation. These may include repainting lines, adding vehicle-to-infrastructure communication and navigation capabilities, or rebuilding complex traffic intersections to be simpler for AVs to navigate. These costs are difficult to estimate, because the extent of necessary changes is unknown, but they will factor into AV expansion. While a company performing an initial deployment of a small-scale Level 4 system may be able to select an operating region in which such investments are not necessary, long-distance Level 4 systems operating over wide areas may require significant infrastructural investment to be feasible throughout the entire operating area.[55] This investment sits alongside other investments in high-bandwidth communication, such as 5G wireless or edge computing systems[56] that may be necessary to support vehicles on the road, if remote monitoring of vehicles is necessary.[57] Such investments can offer a public good by enabling lower-cost autonomy across a spectrum of public and private applications. Different communities might be more or less able to provide such infrastructure improvements, which could lead to inequities in how Level 4 systems are deployed across regions.

Vehicle operational domains

Operational domain—the geographical area a system is designed to use—is another limiting factor for vehicle automation. As discussed above, today's Level 4 systems rely on a variety of infrastructures, and hence are typically deployed in more populated areas. These needs, in addition to the density of potential customers, contribute to a focus on automation in urban and suburban rather than rural areas. Sensing technologies are currently weather-dependent, thus the concentration of testing in sunny areas like California and Arizona.[58] Because of these and related factors, there has been, and will likely continue to be, a strong regional component to the rollout and adoption of fully automated driving systems.

These domains matter on smaller scales as well, right down to the level of individual streets or neighborhoods. Domain limits are not generally made visible in predictions of AV progress due to a common assumption that Level 4 systems can operate in "most places" that a human can drive. Actual operational domains for Level 4 systems, however, are currently much more limited. The domains in which automation systems operate are distinct and not necessarily interchangeable. Therefore, automation level alone is not a sufficient description when considering the mobility or employment impacts of automated driving systems.

Geofencing[59] is a term used in the AV community to refer to limiting autonomous operations to a predefined area—a "geographical fence." The geofenced area might include certain streets within certain areas, based on map coverage and intersection complexity. Geofencing makes Level 4 system deployments possible in the near term, but also limits impacts to areas in which conditions are favorable.[60] Difficult problems include complexity differences between urban and highway driving, regional differences in infrastructure and driver behavior, and navigating particular intersections with poor visibility or unusual configurations.[61]

All roads are not created equal. Quiet side streets with lower speed limits (e.g., 25 mph) are typically easier to navigate than busy urban arterial roads with higher speed limits (45 mph or higher). Turns across traffic at intersections without traffic signals or clear lines of sight are more difficult than turns at intersections with signals and good visibility in all directions. Narrow driving lanes with adjacent parked cars and/or overgrown roadside vegetation are more difficult to negotiate than wide lanes with a clear shoulder. Limited-access highways provide a more predictable environment, though road construction or debris in the roadway can flummox perception and prediction systems.

Local policymakers must therefore ask about the operational domains for these systems.[62] What kind of streets make up a geofenced area? What infrastructural changes would be necessary to expand such areas? A Level 4 system that operates in an office park, for instance, is not technically equivalent to a Level 4 system that operates on a fixed loop with some protected right-of-way, or one that services all streets in a small downtown area or only on a regional highway network. Just because a vehicle achieves Level 4 autonomy in one neighborhood does not mean that other nearby neighborhoods would follow quickly. It is therefore likely we will first see limited-route Level 4 AVs in urban and suburban areas, with slow spread toward wider geographic adoption.[63]

The high costs, local nature, and slow rollout of foreseeable Level 4 autonomy has several implications. First, local policies will play a central role in regard to infrastructure spending and testing—varying economic, political, cultural, geographic, and weather conditions across the country will shape the nature and speed of adoption. And second, the wholesale replacement of public transit by automated cars or taxis seems highly unlikely. That said, we see possibilities to integrate AV technology into existing mobility systems, as feeders to public transit or as parts of bus systems.

Four Possible Mobility Futures

To consider the employment effects of automated driving technologies within these complex ecosystems, we examine four specific scenarios:

1. DRIVER-ASSIST PERSONAL CARS

Consider a future of active safety features that complement human driving and offload driving tasks. Automated driving technologies, such as automatic lane keeping and adaptive cruise control, have already begun to enter a wide cross-section of personal vehicles over recent years. Feature-level improvements are likely to continue with the introduction of new kinds of automation assists. These include traffic jam assists that allow hands-off (Level 3) operation at slow speeds in highway traffic, or on-ramp to off-ramp Level 2 systems for particular highway routes. Reductions in prices of automation options packages and their provision on less expensive vehicles will be a key enabler for adoption. Level 3 systems will likely be limited to lower speeds, since at higher speeds limited sensor range reduces available reaction times, making it more difficult to predict the behavior of other vehicles.[64]

2020 had been forecast to be a critical year for automakers' own predictions of highly automated features, including Volvo, Audi, Subaru, Renault–Nissan–Mitsubishi, Mercedes, Toyota, Tesla, Waymo, and Groupe PSA.[65] The impact of COVID-19 on some of these projections remains to be seen, but already the dates for some planned deployments have been moved back in time.

The development of active safety and low-level automated driver assistance systems provides numerous technology and software jobs within the automotive industry, numbers that are expected to grow in the future. The European Union's report on vehicle automation projects both an increase in the number of openings for computing professionals as well as the emergence of new professions or specialties within automotive technology fields, at high skill levels.[66]

Active safety may combine with other trends toward electrification and connected vehicles that would, for instance, increase the provision of OnStar-like remote assistance systems that require call-center type services, employing workers with less technical expertise.[67] These systems will contribute to changes in the work of professional drivers, but do not necessarily impact job numbers to the extent that other systems might, because Level 2 and Level 3 automation systems do not remove drivers from vehicles.

Increases in the availability and capability of active safety systems may further increase vehicle-miles traveled for personal vehicles, over and above the projected 10% per decade increase in vehicle-miles traveled due to population and income growth.[68] This impact would be a result of greater driving convenience.[69] A National Renewable Energy Laboratory study showed a large range of potential energy usage impacts from automation, from a 60% decrease to a 200% increase, depending on how easier travel radically alters consumer driving behavior.[70] In a vacuum, therefore, increasingly automated personal cars could lead to increased congestion and emissions. Also, transit ridership might decrease for segments of the population who can afford the new vehicles. However, driver-assist personal vehicles will not exist in a vacuum; rather, they will appear alongside other modes of automated driving and coexist with other types of transportation, including bicycles and buses, sharing the roadway.

2. AUTOMATED TAXI FLEETS

The only automated taxi fleets that currently exist are pilot programs run at small scale. Even these, with the exception of a subset of Waymo's vehicles in Arizona, still operate with safety-drivers in the vehicles, who must actively supervise the systems at all times.[71] Note that Waymo has said that it employs remote fleet operators who actively monitor mission progress from a remote location.[72] It has been reported that Waymo sometimes uses a "chase van" to follow a vehicle during empty driver seat missions.[73] As in all airline cockpits where pilots monitor complex automation systems, today safety-critical automotive systems almost always have a human actively monitoring the system in some way, at some location, even if not physically present.[74]

As with Level 2 systems for personal vehicles, highly automated taxi fleets, as they begin to arise, will generate technology and software jobs. Unlike for Level 2, the employment implications of automated taxi fleets to professional drivers are potentially large. In combination with reliable connectivity infrastructure, however, Level 4 systems open up a range of new remote monitoring roles. In some cases, remote driving systems could move driving jobs from vehicles to fixed-location centers,[75] but these might represent a step down in job quality for many professional drivers.[76] It is also likely that fleet services and teleoperations will create new jobs of other kinds in management centers.[77] The skills required for these jobs is largely unknown, but they are likely to be a combination of call-center, dispatcher, technician, and maintenance roles with strong language skills.[78] More advanced engineering roles, such as safety case development and evaluation,[79] could also be sources of good jobs if automated taxi fleets are deployed at scale, but they will require strong technical training that may be out of reach for many.

However effective they might be, automated taxi fleets will likely serve as extensions, not replacements, to existing taxi and ride-hailing business models. In the near future, the geographically limited domains in which Level 4 systems can operate mean that fully automated trips will be constrained to particular neighborhoods or previously mapped transit corridors, such as between an urban downtown and its airport. Flexible human drivers can be expected to serve trips outside of these corridors, or under adverse weather conditions, as they have done in some automated vehicle pilot projects so far. These will be supplemented by low-speed autonomous shuttles, as described below.

If automated taxi services, especially electrified ones, do capture significant market share from the personal car, they could have significant impacts on the auto industry as a whole.[80] Vehicle production may slowly shift toward purpose-built electric mobility service vehicles, with impacts felt across supply chains. Still, personal cars will survive alongside these systems for decades. Recent modeling of city-level mobility patterns suggests that a mature automated taxi system might capture only 6% to 16% of total trips, depending on geography and the availability of mass transit alternatives.[81]

Many people enjoy driving—at least when they are not stuck in traffic—and form close attachments to their personally owned vehicles.[82] The convenience of cars for many users is not just about personal mobility, but also about identity, class status, and carrying and storing the materials of everyday life—such as strollers, golf clubs, and kids' sports equipment. Shared vehicles are less suited to these uses,[83] so the potential of mobility service AVs to directly replace customers' personal cars is likely overstated.[84] Still, ride-hailing may already be reducing public transit usage, and automated taxis will continue to challenge transit systems and their employees.[85]

If fleet-based Level 4 AVs do successfully reduce the cost of transportation, as proponents claim, they—like driver-assist personal cars—may induce the demand for more trips.[86] Studies on the relationship between travel costs and miles-traveled or public transit usage suggest that transportation use is responsive to price.[87] In general, vehicle-miles traveled increases as cost and effort of travel decrease. But, mobility services that are pay-by-mile no longer hide the real cost of trips in the cost of overall ownership, an effect that might change trip frequency, or reduce vehicle-miles traveled, in different ways than for personally owned vehicles.[88] Estimates of price elasticity based on Uber data suggest that demand is not highly sensitive to small changes in price at the low end of the price scale, which suggests that less expensive automated taxi rides might not generate a significantly greater number of trips.[89] Moreover, projections based on actual costs of taxis today suggest that high occupancy will be needed for automated taxis to be price-competitive with personal vehicle ownership. Consumers generally share a "strong aversion" to multiple-occupancy taxi trips.[90] So, on balance, automated taxi fleets are likely to complement and not dominate urban mobility.

3. AUTOMATED SHUTTLES AND BUSES

Consumers do, however, already expect and indeed tolerate high-occupancy trips on public transit systems like trains, subways, shuttles, and buses. Thus, increasingly automated public transit is an important trend to consider alongside driver-assist personal vehicles and automated taxi fleets. While cities themselves are not the prime movers in this space today, private enterprises like May Mobility, Optimus Ride, and Navya have been collaborating with cities and the private sector to begin offering medium-occupancy shuttle services on fixed routes using automated vehicle platforms.[91]

A number of factors combine to make public transit a promising area of application for automation. As we have established, highly automated vehicles are first appearing in strictly geofenced operations, which more closely fit the public transit model of fixed routes. Furthermore, geofenced areas will be extended not simply by improved automation technology, but also by reshaping the roadway infrastructure to be easier for automation to handle. Continued infrastructure investments necessary for AV projects likely imply employment increases in maintenance of roads and systems, if funding is made available, as has occurred in California.[92] These investments align with some of the needs of public transit systems, which already employ protected guideways for buses, as well as special lights, signs, navigation systems, and laws to make it easier for buses to get around on public streets.

Thus, it is a mistake to assume that AVs will render urban mass transit obsolete.[93] When complementing instead of supplanting mass transit, increased automation will engender similar employment shifts as in the taxi model: away from driving, toward remote supervision and IT. In the case of buses, however, it will be employees within public transit systems, rather than taxi or rideshare drivers, who will be affected. The outcomes here will depend on the relationship between fixed costs (capital) versus variable costs (labor and system operating costs) in a particular region, mitigated by road use and congestion concerns.

Level 4 bus systems offer the greatest promise for positive transit and environmental impact. Even compared to automated taxi systems, automated buses offer greater occupancy. Moreover, they amortize the environmental costs of vehicle production and disposal over the greatest number of miles and person-trips during their life cycles. Accurate environmental cost estimates would depend on robust estimates of changes in travel patterns based on yet unknown shifts in consumer behavior.[94] But, buses are already much more efficient at moving people than are private cars. Increases in vehicle-miles traveled and trips on buses will also not increase traffic congestion in the same way that a proliferation of mobility service vehicles would, and so this future would be better for other users of urban spaces. Some argue that the automated electric bus is the single most promising technology for impacting mass transit.[95]

Other authors suggest the importance of using price pressure on personal vehicle ownership or single-occupancy trips to move consumers toward more environmentally and socially conscious forms of mobility. A reliable, widely available, and attractive public transit system (along with the cost and difficulty of finding parking) is already one of the key disincentives for the ownership and use of personal vehicles.[96] Automation technologies can accelerate this process by reducing costs of bus operation, or by providing a denser network of destinations around transit hubs (although even in this scenario, personal vehicles continue to be necessary for mobility in suburban and exurban areas).

It is critical, however, to be aware of the potential unintended consequences of such a deployment. For example, Naumov et al. recently developed a system dynamics model to study the effect of automated vehicles and pooling on transit, and concluded that “the deployment of AVs and pooling can be effective at accelerating the transition to sustainable urban mobility, but only when accompanied by policies that make driving less attractive, not more.”[97] Further analysis of this type is needed to study the interplay among AVs, transit, ride-share, and private vehicles in myriad settings.

In the short term, due to the COVID-19 crisis, social distancing and other safety measures may have the effect of reducing public transit's capacity, which will place more pressure on states and cities to deploy technologies that will improve capacity in existing systems. In the long term, the crucial role of public transit for connecting workers to workplaces will endure: The future of work depends in large part on how people get to work.

4. LONG-HAUL TRUCK PLATOONS

Beyond moving people, the movement of goods on public roads is another primary use case for automated driving systems. Many believe that in the near term, increased automation will bring much greater impacts to trucking than to passenger-carrying vehicles. Numerous reports specifically address the implications of AVs for long-haul trucking, because it is the source of a large number of middle-class jobs for workers with diverse educational backgrounds.[98] With approximately 2 million truck-driving jobs in the United States, the potential employment impacts here could be significant.[99]

From a technical perspective, trucking is promising as an early use case due to the relative simplicity and consistency of highways in comparison to crowded city streets. Accordingly, investment in Level 4 automated trucking has been strong in recent years, with companies such as Embark Trucks[100], Ike[101], Kodiak Robotics[102], TuSimple[103], and Waymo Via[104] reporting significant investments. Some have announced ambitious plans that are reminiscent of some optimistic predictions that were made a few years ago for passenger-carrying Level 4 cars. TuSimple, for example, has stated that it aims to establish Level 4 service from Los Angeles to Jacksonville by 2023, followed by a nationwide Level 4 freight network in 2024.[105]

Starsky Robotics was the first company to perform a highway truck journey without a human onboard, on a 7-mile stretch of highway in Florida in 2018.[106] Starsky, however, shut down operations in early 2020. CEO and cofounder Stefan Seltz-Axmacher has written insightfully on the challenges that he faced in trying to launch a startup in this sector, including the difficulty of supervised machine learning algorithms to deal effectively with edge cases.[107] This despite the fact that Starsky's proposed business model utilized remote supervision of unmanned trucks, which would eliminate many long days and nights away from home for long-haul truck operators.[108]

Steve Viscelli has written an insightful study of employment impacts due to trucking automation, analyzing six scenarios: (1) human-human platooning, (2) human-autonomous platooning, (3) highway-automation with remote control for local operations, (4) highway-automation with the capability for a driver to sleep onboard, (5) highway exit-to-exit automation, and (6) facility-to-facility automation.[109]

Scenario 1, human-human platooning, has already undergone extensive development and testing by Peloton Technology, with the aim of increasing fuel economy and safety.[110] Human-autonomous truck platooning, in which multiple Level 4 trucks follow a human-driven lead truck, may be more viable than completely operator-free Level 4 operations in the near term. Initial truck platooning systems will have limited impact on transport jobs, outside of changing the day-to-day work practices of driving. Drivers will need to acquire and apply new skills of working with and monitoring the automation. Opportunities for upskilling and reskilling, therefore, will coexist with the potential for deskilling, depending on how these systems are implemented with respect to human work roles. The impact of this type of automation on the role of the traditional owner-operator in trucking is unclear.

The possibility identified by Viscelli's scenario 4, in which a Level 4 system would enable a truck driver to sleep in the cabin during part of a journey, has strong economic appeal: If a truck driver can sleep while the automation handles long stretches of highway, the driver can then wake up to handle trickier parts of the journey that occur on local roads. It is important to remember, however, that the autonomy system will sometimes need to handle inclement weather, unexpected construction, or law enforcement officers in the roadway. The physics of handling rare events is arguably more difficult at high speeds on an interstate than at low speeds on a city street, based on sensor range, reaction times, and kinetic energy. It may, indeed, take many years before we see a sufficiently reliable automated system that enables a truck driver to sleep soundly, alone in the cabin for an extended journey, without some sort of remote backup supervision for the autonomous system. As one comparison, we have not yet achieved this kind of automation in cargo or passenger aircraft, despite their operating in a simpler environment.

While the employment implications of widespread Level 4 automation in trucking could eventually be considerable, as in other domains, the rollout is expected to be gradual. Viscelli projects that in 25 years, about 294,000 truck-driving jobs will likely be at risk, with an emphasis on higher-paying jobs.[111] He concludes that "cataclysmic loss of truck-driving jobs is not imminent," but recommends a number of meritorious policy goals, including strengthening career pathways for drivers, increasing labor standards and worker protections, advancing public safety, creating good jobs via human-led truck platooning, and promoting safe and electric trucks.[112]

Overall, as with taxi and bus fleets, humans will not so much disappear from truck fleets as change roles to incorporate supervision of automation as part of the job. These and related shifts will require new skill sets for drivers. Truck drivers do more than just drive, and so human presence within even highly automated trucks would remain valuable for other reasons such as loading, unloading, and maintenance.[113]

Local delivery jobs will not likely be impacted to the same extent as long-haul trucking jobs due to the operational domain issues involved in reaching every household, and the role of the delivery person in moving packages to delivery points. In fact, numerous startups are working on "last mile delivery" robots that seek to deliver food and other packages to people's houses. These robots need to solve many of the same difficult technical challenges of robotics, such as perception, planning, and localization, as encountered by Level 4 robotaxis. Carrying only packages instead of people can lead to simplifications in vehicle and system design. However, locomotion on varying terrain, traversal up and down stairs, and dexterous manipulation remain major research challenges in robotics, as evidenced by the 2015 DARPA Robotics Challenge.[114]

Discussion

These four possible mobility futures help to paint a picture of how autonomous vehicles may develop and change mobility in the near future. Of course, these possibilities raise as many questions as they answer:

What are the likely futures for automated vehicle systems?

We should expect continued proliferation of increasingly advanced Level 2 and Level 3 systems in personal vehicles, with limited impact to jobs but potential impacts to vehicle-miles traveled and congestion, and therefore environmental costs. Level 3 systems will likely be restricted to low-speed traffic due to liability concerns and brand reputation risks. A gradual increase in the number of Level 4 taxi or ride-hailing systems is expected to appear by 2025 and spread across urban areas. We should expect an expansion of increasingly automated truck platoons along long-haul highway routes, as well as an expansion in the uses of automated driving technologies in fixed-route shuttles, buses, and public transit.

What are the likely impacts to mobility jobs, including transit and mobility industries?

Automated vehicle systems will not be jobless. The engineering of automated vehicle systems and vehicle information technologies will open up new roles and specialties in expert, technical fields. However, roles at other levels will also appear. Automation supervision or safety-driver roles will be critical for the development and testing of Level 4 systems. Remote management, or dispatcher, roles will bring drivers into control rooms and require new skills of interacting with automation. New customer service, field support technician, and maintenance roles will also likely appear alongside more complex vehicles and new service models. Transitioning from current-day driving jobs to these jobs represents potential pathways for employment, so long as job-training resources are available.[115]

Wh*at will be the interplay between AVs and public transit?*

AVs can be an effective enhancement to public transit, rather than a replacement for it. In the context of local geography and mobility flows, AV deployments can increase access to public transit as part of a multi-modal transit architecture.[116] As discussed above, May Mobility's pilot deployments of small electric shuttles that connect transportation hubs with nearby commercial developments can fit this model.[117] Many existing transit networks have gaps in coverage, which often result from the complicated history of new projects that can take decades to unfold.[118] AVs can potentially fill such gaps with a much lower capital investment and development time than building a new subway or light rail system, if investments are made to prioritize operations in those areas. A robust public dialog on these topics is essential to ensure that innovation in mobility leads to equitable outcomes. Public transit advocates have voiced skepticism about how potential AV investments should be prioritized in relation to other improvements, such as sidewalk and roadway changes that increase pedestrian and cyclist safety.[119] These voices are important. Cities and state governments should work to shape AV deployments for the public good and to ensure that investments in AVs are balanced against other priorities.

From an employment perspective, Level 4 autonomy will take longer to roll out than many have predicted. For at least the next decade, the employment threat to our nation's more than 680,000 bus drivers is low. We do, however, expect to see increasing numbers of low-speed automated shuttles on city streets; their effect on public transit is intended to be positive, but not guaranteed. Longer term, training for public transit workers to work in concert with new automated mobility systems will be essential.

How quickly will these technologies arrive?

Forecasting technology is notoriously difficult. We can, however, say a few things definitively about AVs based on the current state of knowledge. As we have learned from numerous other arenas of automation, including aviation and manufacturing, developments in the AV sector will take longer, and will carry more uncertainty and risk, than many have predicted.

When upper and lower bounds are given for existing long-term estimates of AV adoption, they are often so far apart as to provide little guidance. For instance, two studies provide high and low adoption scenarios that differ by a decade or more on key market penetration estimates.[120] What can be reliably gleaned from the estimates is therefore the sensitivity of predictions to assumptions about cost, service type, and technology and/or infrastructure improvements that come after the date of first implementation; these are all factors on which policy can have an impact.

In terms of technical knowledge, the expansion of automated vehicle systems is likely to be quite slow, because there is no guarantee that improvements in driving performance will happen linearly or predictably in these varying applications. Current best estimates show a slow shift toward Level 4 systems even in trucking, one of the easier use cases, with only limited use by 2030. Overall shifts in other modalities, including fleets and passenger cars, are likely to be no faster, and so disruption to taxi, rideshare, and bus driver jobs is likely to be limited in the near term.

Groshen et al. recently studied projected employment changes in the United States under the assumption that *all* driving would be fully automated by 2050.[121] This is extremely unlikely to occur. The ability for Level 4 technology to be deployed safely at scale remains unproven, and liability concerns may further slow the speed of deployment.

Tremendous safety gains for human-driven cars, however, do seem achievable on this time scale, using all the technologies in the automated driving toolbox. Under the paradigm of human augmentation rather than human replacement, the nation should set the goal of reducing traffic injuries and fatalities by several orders of magnitude. As Pratt has described in his vision for Toyota's Guardian,[122] dramatically improved driving safety is likely within our technological reach, even if humans remain behind the wheel.

Enhanced R&D investments in the core technologies that underpin automation can help our country to achieve dramatic road safety improvements while also enhancing U.S. competitiveness in robotics and related fields. As highly automated systems penetrate daily life, we advocate for human-centered approaches that seek to augment, rather than to replace, human capabilities—not only in the car itself but also within the broader context of streets and cities.[123] We need fundamental advances to realize systems that can predict and anticipate human behavior in complex environments, such as a crowded urban intersection at rush hour, and that can be generalized to other important problems.[124] Research is needed in areas such as robust perception and planning, human-machine interaction, novel sensing technologies, self-supervised machine learning, spatial AI, smart city infrastructure, and large-scale distributed mapping and localization. Opportunities abound for innovative small businesses to contribute in these areas, though the core problems in autonomous driving are the core problems of AI itself: How do machines sense, interpret, and act in the human world?

Forging a Pathway Forward

A disruptive shift to complete automation in the space of a few years would put the livelihoods of millions of middle-class families at risk, but a less disruptive shift would provide time for adaptation, job training, and natural shifts in employment. This less disruptive future is the one we are likely to witness. A slower shift will provide time to ready policy for automation change; nonetheless, it is imperative to act now to prepare. Below are high-level policy ideas that are already being implemented or considered across the country.

POLICY RECOMMENDATIONS:

1. **Investment in public transit and public infrastructure** will be as critical to the new mobility as it is for the old mobility. At a national scale, infrastructure investment in the highway system will aid Level 4 automation for trucking and long-distance routes. If urban centers are among the main places where Level 4 mobility service technologies will be effectively released, states and cities should also be prepared. The right infrastructure investments will provide benefits to multiple forms of mobility: public and private, mass and individual. A long-term shift in mobility mix in cities will not be an outcome of technology alone, but will depend on how transit policy is structured. Public-private collaborations to maintain and invest in the infrastructure needed for Level 4 systems are promising, but must ensure that public entities are not saddled with disproportionate risks.[125] Furthermore, AVs must be thought of as one among many mobility options requiring investment, and must be integrated into regional transit systems. AVs can become enhancing feeders for public transit rather than replacements, but only if cities undertake efforts to mitigate unintended consequences.[126]

2. **Public and private-sector leadership should engage with local communities** to manage expectations and incentives. While there are reasons to assume that AV will be neither as cheap nor as widespread as once predicted, and thus less disruptive, economic and social incentives remain powerful tools to shape mobility patterns for the greater good. We make no particular recommendations for or against road-pricing, congestion charges, low-occupancy taxes, or other methods of pricing mobility externalities into service costs. However, these are all options for states and cities to consider. Community dialog is essential to involve stakeholders in the deployment of mobility innovations.

3. **Workforce education and training** must be part of a holistic response to technology and mobility change. Employment shifts are most likely to affect trucking jobs first, and taxi and transit jobs at a later date. A spike in the number of safety-driver jobs for AVs, as testing accelerates, is a potential pathway for some drivers to enter the emerging industry, as is remote driving. Other drivers will need to retrain to meet the needs of new jobs in fleet management. And, new generations of high-school and college graduates can prepare for jobs that involve increasing interaction with automation systems. Continued investment in workforce training, or other strategies to address job and market change, is critical. We support the development of community college programs that are flexible and responsive to technological change to educate and retrain workers for autonomy-related occupations. We echo others' calls for engaging technology developers and members of the workforce in discussions about needs and skills. Sharing information not only will help workers better prepare themselves—but also will help ensure that the jobs created are good jobs.[127]

COVID-19 IMPACTS ON AUTOMATED VEHICLES, MOBILITY, AND JOBS

The COVID-19 crisis dealt a harsh blow to public transit and ridesharing, with the use of public transit falling by more than 70% in New York and other cities,[128] although as of this writing those numbers are already beginning to return. Uber and Lyft suffered sharp declines in their ridership.[129] The adverse impacts to public transit from COVID-19 have exposed and exacerbated the existing inequities in mobility and employment in cities. Low-income workers rely more on public transportation and are less likely to have access to private vehicles for commuting.[130] They are also less likely to be employed in occupations that enable them to work from home—reinforcing that any future mobility plans must include public transit and discussions of land use to be equitable.

After COVID-19, it is likely that more people will work from home than in the past.[131] Some who must commute, however, may be more likely to drive personal vehicles to work instead of choosing public transit or rideshare—although many will not have that choice. Increased use of bicycles and scooters is also expected. Still, robust public transit systems provide the access and security that low- and middle-skill jobs of the future in other domains will require. Again, the future of work must include how people get to work.

Level 4 robotaxi operations may suffer some of the same difficult perceptions of transit and rideshare in a post-COVID-19 world. Increased cleaning requirements between uses of an AV might be yet another cost to consider in pursuit of a profitable robotaxi service.[132] However, automatic cleaning with ultraviolet light has been used in other settings.[133] During the crisis, despite their notions of "driverless" operation, automated vehicle companies largely paused their on-road operations due to the physical proximity of safety drivers and engineers in their cars, and instead placed a renewed focus on simulation.[134] Cost pressures on the automobile industry and startups could lead to increased consolidation of AV efforts.[135]

With the surge in e-commerce brought on by COVID-19,[136] interest in robotic package delivery companies such as Nuro[137] and Starship[138] has increased. COVID-19 may accelerate investments in robotic technologies that seek to move products through the world with seemingly effortless efficiency; it is important, however, to remember the human workers who fill critical roles in such systems, often behind the scenes.

The geographical rollout of Level 4 automated driving is still expected to be slow due to the various technical and other challenges described above. Human workers will remain essential to the operation of these systems for the foreseeable future, in roles that are both old and new. Ensuring a place for human workers in the automated mobility systems of the future is a key challenge for technologists and policymakers as we seek to improve mobility and safety, and thereby opportunity, for all.

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