Taming the Autonomous Vehicle
A Primer for Cities

Bloomberg Philanthropies
THE ASPEN INSTITUTE

“The advent of autonomous cars is one of the most exciting developments ever to happen to cities—and if mayors collaborate with one another, and with partners in the private sector, they can improve people’s lives in ways we can only imagine today.”

Michael Bloomberg, philanthropist and three-term New York City mayor

“Cities are natural sites for collaboration that leads to innovation. This partnership between the Aspen Institute’s Center for Urban Innovation and Bloomberg Philanthropies is a wonderful opportunity for mayors, technologists, policy experts, and thought leaders to apply technology to make cities safer, healthier, and better connected. The real innovation potential here is not just for new kinds of cars, but new kinds of communities.”

Walter Isaacson, President and CEO of the Aspen Institute

The Bloomberg Aspen Initiative on Cities and Autonomous Vehicles will help 10 leading global cities better prepare for the era of autonomous vehicles. The initiative is one of Bloomberg Philanthropies’ Government Innovation programs that equip mayors and other city leaders with the tools and techniques they need to solve urban challenges and improve citizens’ lives.

Throughout 2017, Bloomberg Philanthropies and the Aspen Institute will convene these cities’ leaders, global policy experts, and representatives from the private sector to explore the intersections of autonomous vehicles with various policies and issues—from the opportunities autonomous vehicles can create to address inequality and improve mobility, to the potential challenges they pose to commuting and public transport. To help a broader set of cities plan for their own future, this initiative will publish a set of principles, resources, and tools that respond to the tremendous interest and needs of cities around the world.

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About Bloomberg Philanthropies

Bloomberg Philanthropies’ mission is to ensure better, longer lives for the greatest number of people. The organization focuses on five key areas for creating lasting change: Public Health, Environment, Education, Government Innovation and the Arts. Bloomberg Philanthropies encompasses all of Michael R. Bloomberg’s charitable activities, including his foundation and his personal giving. In 2015, Bloomberg Philanthropies distributed $510 million. For more information, please visit bloomberg.org or follow us on Facebook, Instagram, Snapchat, and Twitter @BloombergDotOrg.

About The Aspen Institute

The Aspen Institute is an educational and policy studies organization based in Washington, D.C. Its mission is to foster leadership based on enduring values and to provide a nonpartisan venue for dealing with critical issues. The Institute has campuses in Aspen, Colorado, and on the Wye River on Maryland’s Eastern Shore. It also maintains offices in New York City and has an international network of partners. For more information, please visit AspenInstitute.org or follow us on Twitter @AspenInstitute.

Initiative Cities

1 **Los Angeles, USA** is a leader in planning for the AV transition, with the adoption of a pioneering comprehensive transportation technology strategy in 2016. As the world center for automotive design, and the cradle of car culture, the region will be an important lab for understanding consumers' views of AVs.

503
3,971,883
8,282
700

2 **Austin, USA,** one of North America's fastest growing cities, was also the world's first site for large-scale testing of AVs, following Google's deployment of test vehicles on city streets in 2015. This year, the city is working to pilot an AV people mover to demonstrate last mile connectivity between a transit stop and several key destinations.

271.8
931,830
3,359
830

3 **Nashville, USA** is a city where AVs will be an essential key to two ambitions—to nurture the region's large and growing automotive sector, which led the state's post-recession recovery, and to restructure the region's transportation system under a plan adopted in 2010. Due in April a Mobility Action Plan will outline a vision for the integration of AVs and future transit investments.

525.94
678,889
1,300
880

4 **Washington D.C., USA** is transforming itself into a leading testbed for automated logistics. Estonia-based Starship Technologies began testing its rovers on city sidewalks in January 2017 with e-commerce partner Postmates. Automated delivery tests under the city's Personal Delivery Device Pilot Program are restricted to no more than five vehicles per vendor, a 50 pound vehicle weight cap, and a 10 mph speed limit.

68.34
681,170
9,967
470

5 **Buenos Aires, Argentina** is an internationally-recognized innovator in bus rapid transit and open government. The city will enter the AV transition in 2017 as it hosts the first of 10 "Formula E" races featuring high-performance self-driving cars.

78
2,890,151
37,000
320

6 **São Paolo, Brazil,** the traditional hub of Brazil's automotive industry, was an early leader in the AV test circuit, with the first on-road trials conducted in October 2013. The city's technical universities, in partnership with global automakers such as Scania, are spearheading the ongoing development of a variety of AV trucks, taxis, and passenger cars.

587.30
12,038,175
20,496
397

7 **London, England** is host to a portfolio of AV pilots. The GATEway (Greenwich Automated Transport Environment), launched in 2015 by the UK's national innovation agency, is a multi-year research effort testing AV use cases and obstacles. In 2017, two major automakers will begin large-scale tests on city streets.

607
8,673,713
14,290
360

8 **Paris, France** is taking a coordinated citywide approach to AV planning, spearheaded by the city's Mobility Agency. An initial pilot with AV minibus maker Easymile will test driverless shuttles on several routes, including a dedicated lane crossing the 800-foot (250m) span of the Charles de Gaulle Bridge. AVs are a key element in the French government's ambitious 'New Industrial France' policy launched in 2016, which cleared the way for future efforts.

40.7
2,229,621
55,000
390

The 10 cities participating in the Bloomberg Aspen Initiative represent a spectrum of urban conditions and are preparing for the AV future in equally diverse ways.

9 **Helsinki, Finland** is a global leader in the smart city movement, and is pioneering a holistic approach to AVs. One of the world's first AV public transit pilots, SOHJOA, tested a quarter-mile microtransit route in the city's Hernesaari waterfront district. The city's recently appointed Chief Design Officer will oversee cross-cutting efforts to integrate AVs into the urban environment.

276.25
635,591
3,783
328

10 **Tel Aviv, Israel** has rapidly emerged as a world-leading hub for digital automotive technology innovation. Sources of new inventions include both homegrown startups like AV powerhouse Mobileye, a supplier of computer vision systems, as well as a constellation of new research centers set up by Japanese, American, and European automakers.

20
432,892
21,638
365

Key to Symbols

Land Area (sq miles)
Population
Density (persons / sq mile)
Passenger Cars per 1,000 persons

Six Big Insights

We've combed through the most insightful reports, forecasts, and announcements to produce this compact primer on the future of cities and autonomous vehicles. It is a scan of the future horizon, indicating clear directions of change where there is strong consensus among leading experts.

Today, there are more than 1 billion cars and trucks on Earth. By 2030, this number could surpass 1.5 billion. Just 5 million of these will be autonomous vehicles (AVs). But from this small start will come a sea change that is expected to completely transform how we travel, the shape of our cities, and the way we live.

Taming the autonomous vehicle, to maximize the benefits and minimize the impacts, will be one of the most important challenges of the 21st century. Here's our cheat sheet of the biggest insights for cities.

1. There is a narrow window to shape the spread of AVs.
Over the last 30 years, automakers and academics laid the foundations for the breakthroughs that are now upon us. AVs will spread slowly at first, but as costs fall in quick fashion, they will spread across the globe even faster than the automobile in the 20th century. Cities could fall behind in the blink of an eye.

2. Automation is changing the automobile, mostly in ways that will help cities.
Cities have long struggled with the car's demands for space. But AVs can be designed for many more forms and functions, creating new opportunities to right-size vehicles for urban use.

3. Automated highways are an obsolete vision of the future.
Most AV pilots in the last decade focused on high-speed highways. But the AV's future is in cities, where its biggest market demographics are concentrated. City driving will be a tough technical challenge but a far bigger commercial prize, increasing demand for real-world urban testbeds.

4. AVs are a vital technology for enabling populations to age in place.
By 2030, the world will be home to more than 1.4 billion people age 60 or over. As the spread of AVs reaches peak intensity in the 2030s, this group will shape the AV market. For cities, AVs will allow more people to age in place and stretch public spending on their well-being.

5. Cities have an opportunity to focus private sector AV innovation on urban challenges.
Both the tech industry and traditional automakers see great opportunities in cities, and the competition will be fierce. Cities can shape markets to focus private sector attention and investment on the needs of cities and the people who live in them by mobilizing infrastructure, talent, and other assets to support the right kinds of AV-based solutions.

6. The implications of AVs will cut across every facet of government, society, and the economy.
AVs promise significant improvements in urban transportation. But the full range of benefits and risks of cheap, automated mobility are yet to be fully understood. In order to maximize the good and minimize the bad, cities will need to tap many sources of expertise inside and outside of government.

The Great AV Transition

Cities are at the crossroads of an historic shift in the technology of transportation. But will it be an incremental update or a full system upgrade?

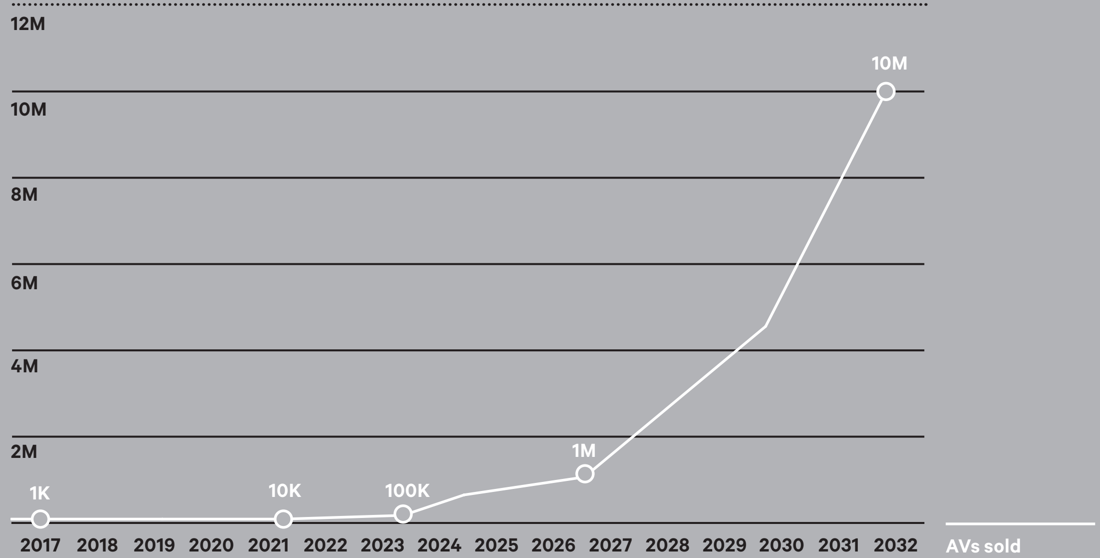
2016 was a watershed year in the development of AVs, with announcements about new products, business deals, and pilot projects on a daily basis. Automakers snapped up AV startups in North America and committed to ambitious plans to produce their first driverless vehicles. A self-driving truck made the first rolling commercial freight delivery in Colorado. Then a drone in Cambridge, England made the first flying one. Ominously, the first fatal crashes attributed to advanced driver assist systems occurred in the United States and China.

But just as it seemed the future was driving away from growing commitments to walkable cities and mass transit, AV technology and the sharing economy hooked up. Self-driving minibuses launched in cities across Europe, while AV taxis rolled onto streets in downtown Pittsburgh and Singapore's high-tech town, one-north.

Accelerating Change

The pace of AV innovation isn't likely to slow for decades to come. In so many ways, the world of 2050 is clearer than the one of 2030, when the transition will be in full swing. In just the next few years, one thousand AVs will give the world its first glimpse of the driverless future. But in less than ten years, over a million are expected to be in use worldwide. **(FIG. 1)**

FIG. 1 After A Slow Start, Sales of AVs Will Takeoff



Source: IHS Automotive

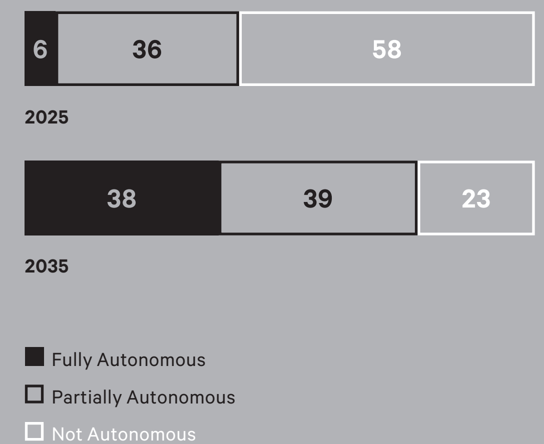
And that's when things will get really weird, as the roads become home to a hodge-podge of human-steered, partially autonomous, and fully autonomous vehicles. We won't know by looking at a car, who or what is truly behind the wheel. **(FIG. 2)**

> "There is a naïve view that AVs are in themselves beneficial. They can be beneficial only if we deliberately make them so."

Peter D. Norton, author of *Fighting Traffic*

FIG. 2 Human Drivers Become the Minority

Vehicles in Service, Worldwide (%)



Source: Boston Consulting Group

What's Here

This horizon scan is a survey of the next 15–20 years, covering the period when the AV transition will spin up to full intensity, but before its history is fully written.

The focus here is not on open speculation but assessing the state of our collective foresight. What are the big trends taking shape, and what is the consensus among experts about the nature and pace of future developments? In six sections addressing the key characteristics of the AV transition we provide highlights of the latest market studies, academic research, and policy-making efforts around the world.

What explains the basics of key AV technology and data.

How analyzes the market and regulatory forces influencing AV development.

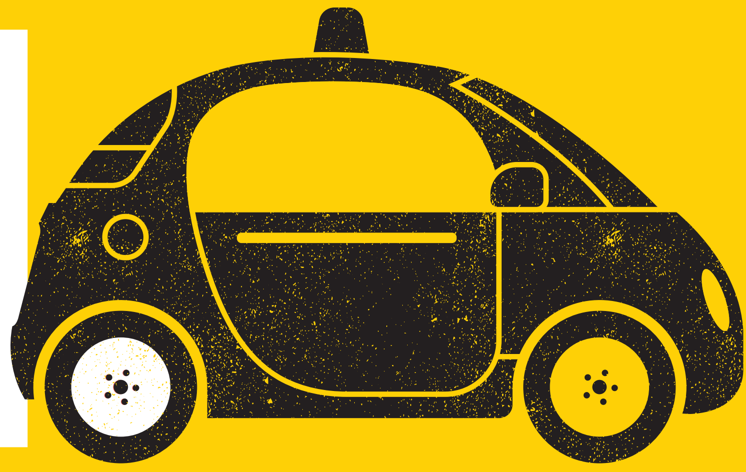
When tracks the historical evolution of the AV idea.

Who profiles the companies bringing the AV future to life.

Where maps hotspots of AV research and where the spread of AVs is likely to occur most quickly.

Why begins to chart the benefits, risks, and unintended consequences of AV technology.

1 what



A field guide to the kinds of AVs that will call cities home in the future, and how they work.

The Many Types of Urban AVs

The private passenger car is the focus of AV speculation. But cities are home to a diverse range of vehicles, which will be automated in different ways on different timetables.

Private AVs won't have free run of future city streets. A wide variety of commercial AVs are already being put into service in pilots and trials around the world, often well ahead of their consumer counterparts. The profiles below highlight a sampling of commercial AVs being deployed in cities across the globe in 2016.

Key to Symbols

- Manufacturer
- Number of Wheels
- Weight
- Number of Passengers
- Current Top Speed
- Pilot Locations

Transport People

- Uber, GM/Lyft, nuTonomy
- 4
- 4,000–6,000 lbs
- 4–6 passengers
- 25–35 mph
- Pittsburgh, San Francisco, Singapore

Autovot / Taxibot

Autovot: AV taxi providing sequential private rides **Taxibot:** AV taxi shared simultaneously by several passengers

- Navya, Local Motors, Easymile, Auro Robotics
- 4
- 6,000–8,000 lbs
- 10-12 passengers
- 25-35 mph
- Lyons, Helsinki, Washington D.C.

Driverless Shuttle

Automated minibus for carrying groups of people over short distances, usually on pre-mapped routes

Transport Freight

- Starship Technologies
- 6
- 40–55 lbs
- 0 passengers
- 4 mph
- Talinn, London, Bern, Redwood City, CA, Washington D.C.

Deliverybot

AV cart providing last-mile light goods distribution

- Otto (Volvo), Scania
- 18
- 33,000 lbs
- 44,000 lbs cargo
- 55 mph
- Colorado, Rotterdam, EU (various)

Software Train

Single or platooned tractor-trailer providing long-haul freight transport

Cybermechanics 101

AVs are supercomputers on wheels. But how will they actually learn to navigate city streets?

For most of their history, cars have been dumb machines. Computers were costly and not very portable. That's why, for decades, approaches to automated driving relied more on smart roads than smart cars. With massive infrastructure upgrades needed, the self-driving future was stillborn.

AI Breaks Through

Then about 25 years ago, research on self-driving vehicles turned decisively in a new direction—autonomous operation. For the first time, computers powerful and portable enough to mount in a car were available. Suddenly, software loaded on a smart car could tackle the challenge of driving unassisted.

Today's AVs are much more sophisticated, packing a breathtaking amount of computational horsepower. For instance, Tesla's Autopilot feature relies on a consumer grade graphics chip, that packs the same punch as the US government's fastest supercomputers at the turn of the millennium. In other words, the CPUs built for nuclear weapons research just a generation ago are now cheap and small enough to drive you to Starbucks.

Vehicular autonomy has important consequences for cities. While work on smart roads continues, these upgrades are no longer the bottleneck on AV deployment they once were. Consumer and commercial AVs are largely being designed to operate on any road a human-driven vehicle can.

"The technology required to drive on the highway versus driving in the city is very different. It's maybe 20 to 50 times easier."

Anthony Levandowski, co-founder Otto

Increments of Automation

To deal with the twists and turns of this journey to full autonomy, in 2014 the Society of Automotive Engineers developed a standard (SAE J3016) to help benchmark levels of automation. This scheme details a continuum of automated driving capabilities from fully directed by humans to fully automated. **(FIG. 3)**

Today's newest car models are already well along this spectrum. Assistive technologies (Level 1) such as anti-lock braking, parking assist, and adaptive cruise control have been introduced gradually over the last 30 years to improve safety and convenience. **(FIG. 4)**

But as they tackle ever more complex driving functions, AVs face a steep learning curve. Driving environments, especially in cities, are extremely complex and change frequently. Construction, severe weather, glare, and other conditions can temporarily blind an AV's sensors or render its digital road maps suddenly obsolete. And operating in close proximity to people means that computers must interpret the subtle social interactions that make movement on streets safe, efficient, and pleasant.

AVs are not as autonomous as their inventors would like us to believe either. As manufacturers confront shortcomings and develop workarounds, they'll be able to continuously address performance issues through software updates. AVs will, quite literally, improve overnight.

Data Fuel and Data Exhaust

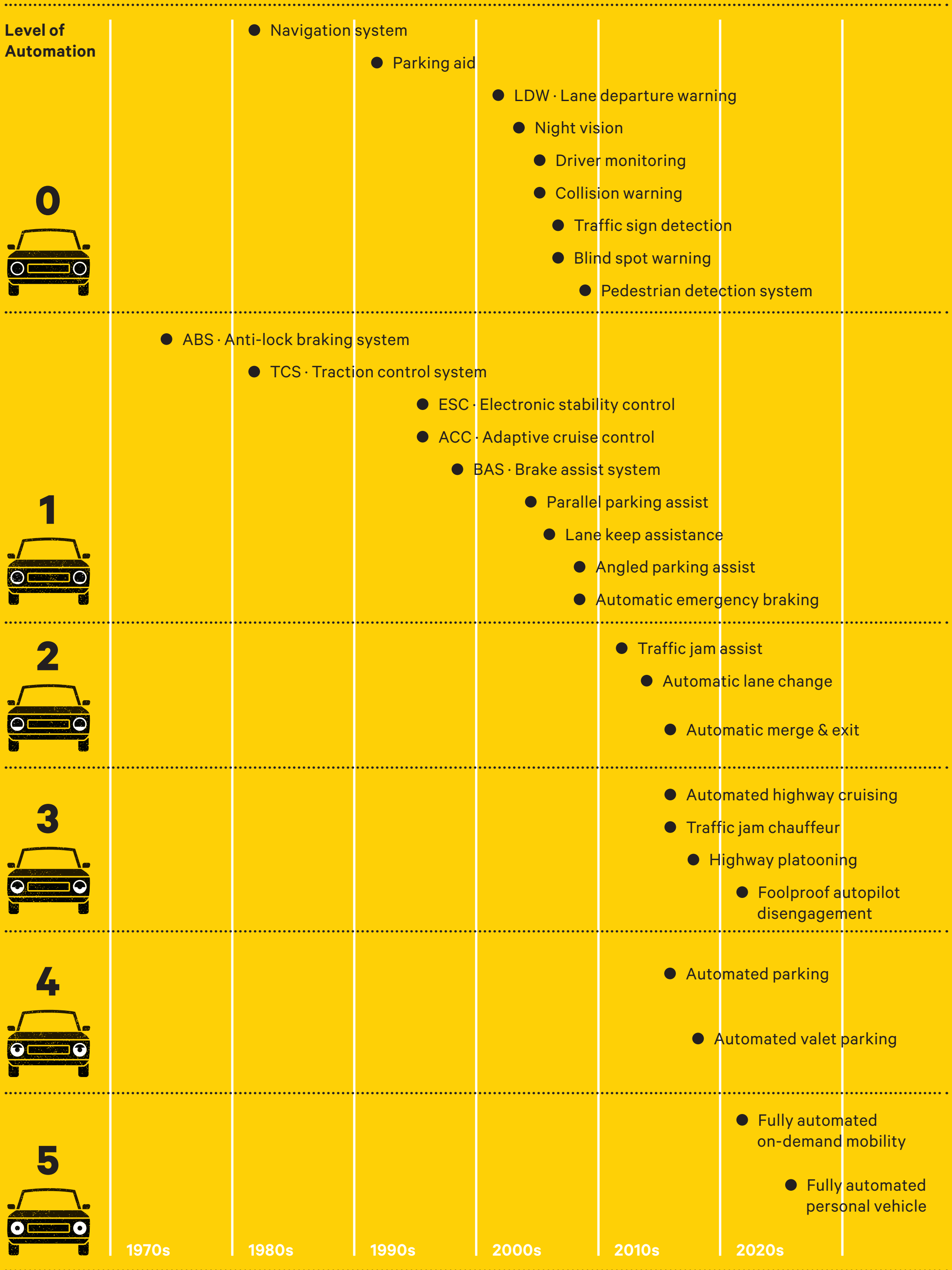
All of that computing power means AVs have a voracious appetite for data, supplied

FIG. 3 The Spectrum of Automated Driving

0	1	2	3	4	5
Human driver monitors environment and controls vehicle; computer monitors for warning purposes only	Computer controls speed or steering only	Integrated computer control of speed and steering	Computer monitors environment and controls speed and steering with full human backup	Computer monitors environment and controls speed and steering with some human backup	Computer monitors environment and controls speed and steering with no human backup

No Automation — **Levels of Automation** — Full Automation

FIG. 4 Incremental Progress Toward Full Automation



Source: Sven Beiker, Stanford University; Various.

by connections to the cloud, onboard map caches, and an arsenal of sensors that a Cold War-era jet fighter would envy. These readings help operate the vehicle but will also be highly sought after by manufacturers, insurers, and regulators to ensure that AVs are operated safely and efficiently.

AVs could be the most important opportunity in history for cities to expand the scope and quality of data they collect about what's going on. The movements of AVs will provide vital insights for street and curb space management. AV taxis will provide vital clues about travel demand. Properly equipped with the right sensors, AVs would be ideal platforms for noise and air quality monitoring.

However, with many types of data streaming off AVs to a variety of destinations, the key challenge will be finding the right incentives and mandates to capture the essentials. A minefield of privacy and security risks will make this even trickier. **(FIG. 5)**

FIG. 5 AV Data Lifecycle

2 when

A timeline showing key milestones and tipping points in the spread of AVs.

Eras of the Automobile

Cities and the automobile evolved together during the 20th century. The next wave of change, driven by automation, will take just a single generation.

Automobiles first arrived in cities in large numbers more than a century ago. Looking back in history as we look ahead to the future, there are three distinct eras in the relationship between city and car: motorization, saturation, and automation. Each encompasses a sweeping set of technological, economic, and social changes. And each has played out more quickly than the last. **(FIG. 6)**

Motorization

Spanning 60 years from the early 1920s to the early 1980s, automobiles began to arrive in large numbers in cities during this period. Local governments, often allied with industry and citizen groups, worked to reorganize streets and land uses around the mobility potential of this new technology. There were few limits to expanding the role of automobiles.

Saturation

As the physical, environmental, and social impacts of widespread car ownership unfolded, the costs of environmental pollution, public health issues, social isolation, and congestion began to outstrip the benefits. Roughly from 1980 to 2020, just 40 years' time, the downsides of car-centric mobility quickly overwhelmed many cities and urban regions.

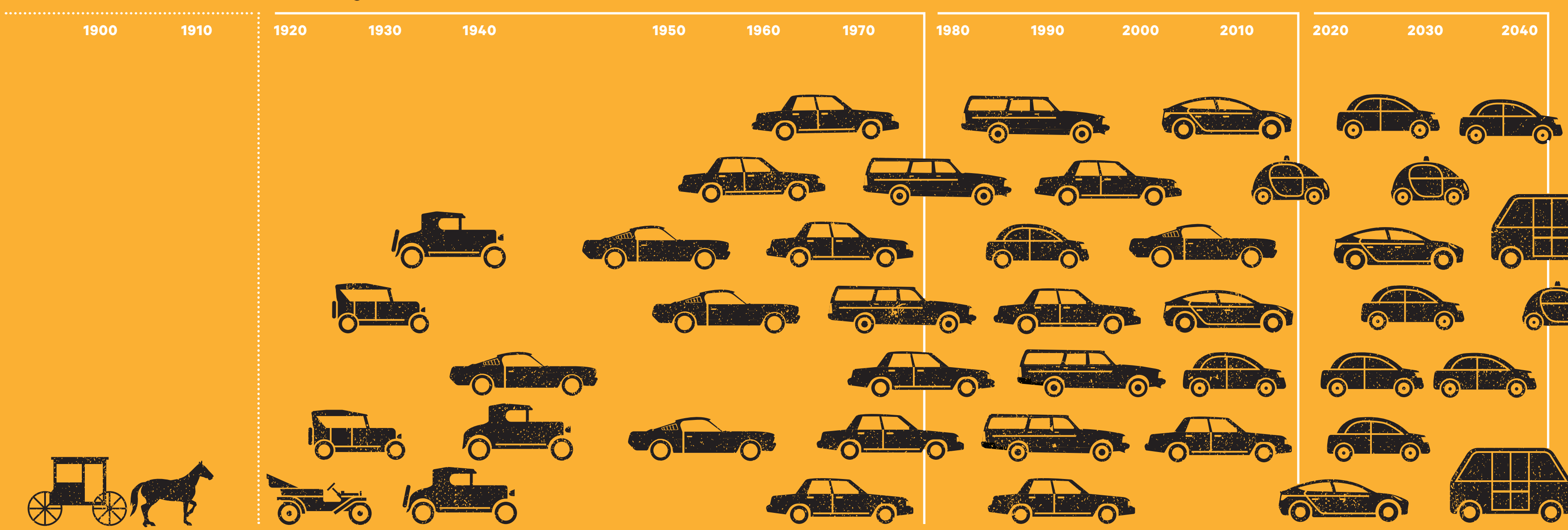
Automation

By 2020, a new era in the union of city and automobile will be underway. Automation will get off to a slow start, but the pace will pick up quickly as the economic momentum of driverless technology spreads widely. The impacts of AVs on cities aren't yet clear—but in just two decades this shift will have run its course, and cities will be committed to the changes that AV markets, regulation, and planning have set in motion.

The horizon for this book is 2030, the midpoint of this era. This is a waypoint sufficiently far off that we can contemplate big changes in business, technology, government, and the built environment. But it is close enough that we can see how the decisions cities make today might shape those outcomes.

Each era encompasses a sweeping set of technological, economic, and social changes. And each has played out more quickly than the last.

FIG. 6 The Automobile's Accelerating Evolution



Technological Tipping Points

The cost of AVs will fall quickly in the 2020s, thanks to breakthroughs in sensor and battery technology.

Just like humans, computerized drivers need to see the road ahead. When Google unveiled its AV prototype in 2014, crowned by a $70,000 rooftop laser scanner, critics decried its high cost as evidence that driverless cars for the masses were far off.

But the price of LIDAR—as the technology is known—is falling rapidly. **(FIG. 7)** Industry analysts forecast that by 2018, when spinning scanners will be replaced by more durable chips, the price of LIDAR will drop below $100. By 2030, this could help push the cost for full autonomy below $1,000 per vehicle.

A second tipping point will come as the cost of batteries for electric vehicles declines rapidly. 2015 was a watershed year for electric vehicles. For the first time, there were more than 1 million in operation worldwide (more than half in the United States and China alone). Despite their growing appeal, however, EV sales have been dampened by the high cost and low capacity of batteries, which limits vehicle range. From 2010 to 2015, the cost of lithium-ion batteries dropped by 65 percent, and it is expected to fall to a long-range cost of just $50 per kilowatt hour, eliminating the price and performance gap with internal-combustion models. By 2040, one in three new cars sold worldwide will be fully electric, according to a forecast published by Bloomberg New Energy Finance and McKinsey. **(FIG. 8)**

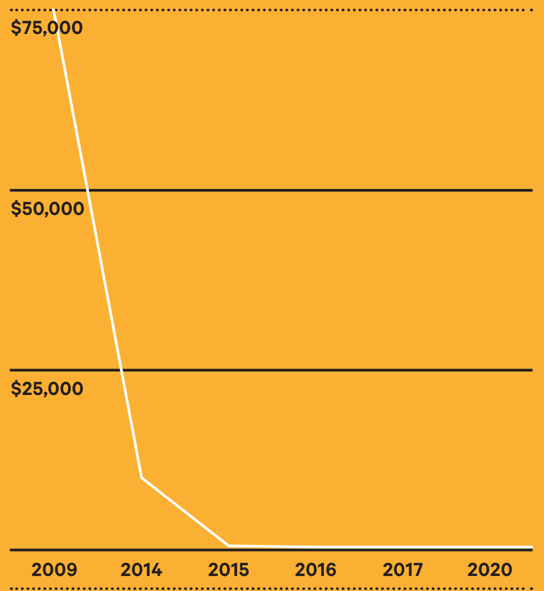
The Symbiosis of AVs and EVs

Why does an uptick in the pace of electric vehicle sales matter for AVs? The fate of AVs and EVs will only grow more intertwined in the coming decade.

In the short run, electric AVs will be cheaper to operate for early adopters like taxi fleets, with fewer parts that must be maintained and lower energy costs. For consumers, as Tesla has demonstrated, these two cutting-edge technologies will go hand in hand—all-electric and all-autonomous will be a powerful package for marketing next-generation vehicles.

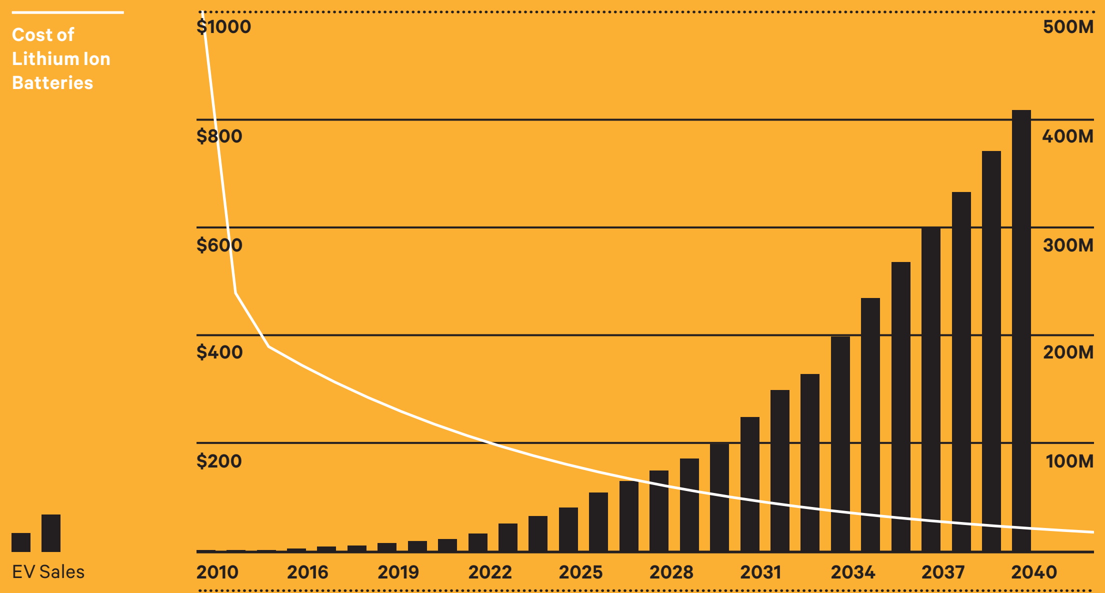
In the long run, electric AVs will be a crucial technology for managing loads on power grids fueled by fickle renewable energy sources. AVs will supply valuable data to allow utilities to predict future demand for electricity as well as the ability to automatically schedule vehicle recharging and efficiently move vehicles around to spread the load more evenly.

FIG. 7 LIDAR Costs Will Vanish



Source: Velodyne, Quanergy

FIG. 8 Electric Vehicles Will Take Over As Battery Prices Drop



Source: Bloomberg New Energy Finance and McKinsey

Future Waypoints

Today is a time of great expectations and apprehensions about the future of cities and AVs. In this timeline, we highlight high-probability events like launch date commitments made by companies and predictions made by experts around watershed AV developments.

While the precise shape of the future is likely to change, these waypoints can help cities begin to plot their journey through the AV transition.

2017

GM begins production of the next generation of its autonomous test vehicles at its Orion Township assembly plant in Michigan.

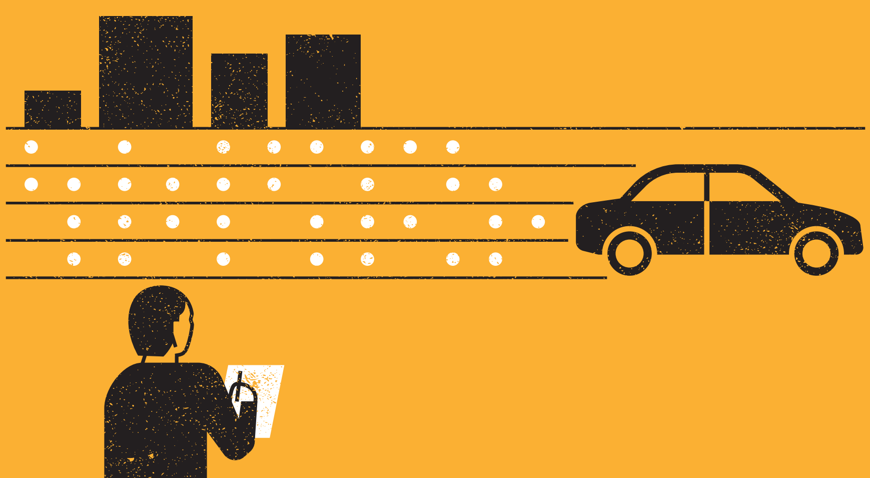
Volvo's Drive Me project, the world's first large-scale, long-term test of Level 3 autonomous cars on public roads, gets underway in Sweden. One hundred drivers spanning various demographic groups and attitudes towards AVs will allow the study of both vehicle and driver performance.

Waymo, an Alphabet spin-off, and Fiat Chrysler begin testing 100 self-driving vehicles capable of Level 4 autonomy on public roads in the United States.

Ford begins testing AV cars of unspecified autonomous capability in Europe. The test comes amid a tripling of the company's R&D spending on autonomous driving.

2017

Cities scramble to establish testing protocols as multiple large-scale consumer AV tests get underway.



2019

Auto component makers Delphi and Mobileye release the Central Sensing Localization and Planning (CSLP), an off-the-shelf Level 4 AV system dramatically reducing the cost of autonomous driving features.

2020

nuTonomy expands self-driving taxi services from Singapore to 10 cities around the world.

Daimler begins offering Highway Pilot, a Level 3 self-driving feature on all new tractor-trailers.

The Tokyo Summer Olympics introduce the world to large-scale vehicle automation for the first time, as Japanese automakers simultaneously launch consumer models and the largest AV demonstrations on public roads to date.

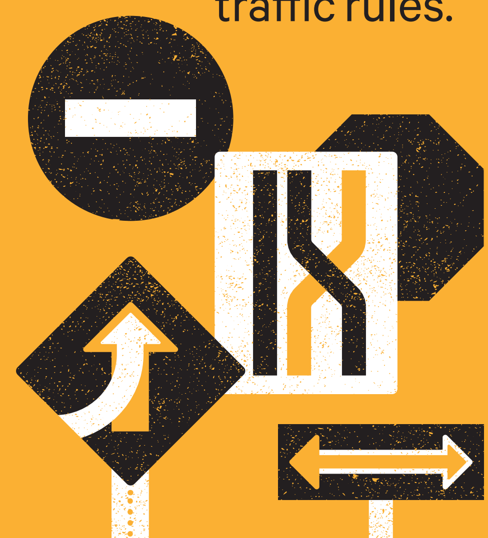
Audi, in partnership with graphics chip maker NVIDIA, start selling a Level 4 consumer AV.

2021

BMW launches the iNext AV/EV in China. The vehicle is introduced with Level 3 capabilities but bundles hardware allowing future software-only upgrades to Level 5.

2019–2021

Increasing numbers of commercial AVs entering cities force a rethink of traffic rules.



2023–2024

Tesla CEO Elon Musk estimates that half of all of new car sales will be autonomous.

2025

Ford launches a Level 4 AV model, potentially one of the first to do away with steering controls.

One-third of new trucks sold worldwide have Level 4 or better, making automation the key profit driver for logistics companies, according to McKinsey.

2028-2032

Robert Hartwig, president of the Insurance Information Institute expects that "it will take 15 to 20 years for truly autonomous vehicles to populate US roads."

2030

Sales of new Level 5 AVs reach 250,000 per year, according to Boston-based Lux Research.

The majority of new vehicle sales in the United States are autonomous—with 42 percent Level 3, and 17 percent Level 4 or 5, according to Goldman Sachs.

Uber completes conversion of entire fleet to autonomous vehicles.

AV/EV buses are widely used in American cities, resulting in noticeable gains in ridership, reduced operating costs, and higher customer satisfaction, according to the National League of Cities.

2023–2030

Full automation of taxi fleets opens the door to major shifts in urban mobility policy.

2035

IHS Automotive analysts predict that autonomous cars account for 50 percent of US and Canadian vehicle sales and reaches 11.8 million in global sales.

2040

Expert members of the Institute of Electrical and Electronics Engineers (IEEE) estimate that 3 out of 4 vehicles will be autonomous by 2040.

2050

Sales of shared vehicles account for 80 percent of a global auto market that as a result is considerably smaller than today, according to a Deloitte scenario.

2050

Uptake of shared AVs has cut parking needs by some 1.4 million acres (567,000 hectares) in the United States, according to McKinsey—an area larger than the state of Rhode Island .

2060

75 percent of all US highway traffic is capable of autonomous driving, according to transportation consultants Fehr and Peers.

2035–2060

Land use reforms capitalizing on ubiquitous AVs take hold, permanently reshaping cities and regions.

3 where

A map of emerging hotspots for urban AV innovation.

Global Rollout

Wealthy nations led early AV experiments, but the biggest future markets will be rapidly urbanizing developing countries. As innovation follows opportunity, megacities in the Global South will export AV designs and uses that create new possibilites for cities everywhere.

Where will AVs take off first? Small, rich countries including Sweden and Singapore have led early efforts to spur development of this new technology. More recently, national governments throughout the developed world have moved to kick-start AV pilots. Today, almost every developed country has launched a pilot. **(FIG. 9)**

From Self-Driving Features to Autonomous Vehicles

Sales of existing driver-assist features can shed light on future demand for AVs. For instance, according to Boston Consulting Group, consumers in Western Europe and Japan are twice as likely to own vehicles equipped with adaptive cruise control technology. By comparison, the United States was about average (6 percent of all vehicles) while in China and other emerging markets these features were less popular.

But the rollout of AVs may be different than single features. The most widely cited forecast on global AV sales, published by London-based IHS Markit, projects that the Americas will account for as much as one fourth of the 21 million (SAE Level 4 and Level 5) AVs sold worldwide each year by

National governments have moved to kick-start AV pilots. Today almost every developed country has launched one.

FIG. 9 Selected National Government AV Pilots

Country	Project	Agencies Involved	Description	Type of Vehicle
Australia 2014	CITI Trial	New South Wales Road Safety Program and National ICT Australia (NICTA)	Evaluation of communication between vehicles and their surrounding conditions.	Tractor-trailers with DSRC
Finland 2015	CityMobil2	European Commission (EC); Finnish Transport Agency; City of Vantaa	CityMobil2 seeks to remove legal barriers and gain insights into how cities may be affected by AVs.	EasyMile EZ10 (Shared, electric 12-person shuttle)
France 2014	CityMobil2	EC; French Ministry of Environment, Energy, & the Sea; La Rochelle	*See CityMobil2 above.	Robotsoft Robucity (Shared, electric 12-person shuttle)
Germany 2016	A9 Autobahn Digitization	Federal Ministry for Transport & Digital Infrastructure (BMVI)	Preparation of the A9 Autobahn for autonomous vehicles.	
Japan 2016	Dynamic Map Planning	Japan Ministry of Economy, Trade & Industry	Developing a dynamic map for accurate AV navigation; self-driving fleets at the 2020 Summer Olympics.	Nissan, Toyota, and Honda are all currently working on autonomous vehicles.
Netherlands 2016	European Truck Platooning Challenge	Dutch Ministry of Infrastructure & the Environment, the Netherlands Vehicle Authority (RDW), Conference of European Directors of Roads (CEDR)	Long-haul automated truck platoons traveling by highway to the Port of Rotterdam from multiple origins in the EU.	Tractor-trailers
Singapore 2016	Delphi Automotive Systems	Singapore Land Transport Authority (LTA)	A three-year pilot featuring six vehicles serving passengers on fixed routes.	Audi Q5 (Personal sport utility vehicle with hybrid engine)
	nuTonomy	Singapore Land Transport Authority (LTA)	Six-car fleet operating a taxi service with predetermined pick up and drop off locations in the one north district.	Mitsubishi i-MiEV (Personal electric vehicle)
Sweden 2017	Drive Me	Swedish Transport Administration, Swedish Transport Agency, City of Gothenburg	Volvo will be testing their AV technology with volunteer drivers on a fixed route in Gothenburg.	XC90 (Personal sport utility vehicle with hybrid engine)
United Kingdom 2015	GATEway	UK Government via Transport Research Laboratory	Testing automated passenger shuttle vehicles as well as autonomous valet parking for paratransit-adapted cars.	Oxbotica (2-person vehicle), Toyota Prius modified by Gobotix
2016	UK Autodrive	Innovate UK	On-road trials of a range of peronal autonomous vehicles.	Jaguar Range Rover, Ford, Tata Motors, RDM Group Pods (two person vehicles)
USA 2015	Mcity	US Dept. of Transportation, Michigan Dept. of Transportation, City of Ann Arbor, Michigan Economic Development Corporation	University of Michigan's test site for autonomous vehicles includes a 15-passenger from NAVYA shuttle that provides self-guided tours of the site.	ARMA (Shared, electric autonomous 15-person shuttle)
2015	Nissan-NASA	NASA	The two companies have signed a five-year agreement to develop autonomous and zero emissions vehicles together.	Nissan Leaf (Electric personal vehicle)

Source: Royal Dutch Touring Club (ANWB)

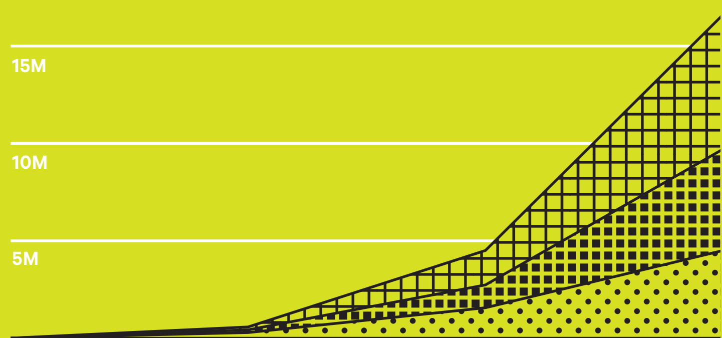
2035. The remaining sales will be split roughly evenly between Europe and the Middle East, Asia and the Pacific, and the rest of the world. (FIG. 10) Worldwide, around 5 percent of all vehicles are expected to be fully autonomous by 2030 (IHS Markit did not forecast market penetration for 2035).

From Global North to Global South
After 2035, China will become the world's largest market for AVs, as sales exceed 6 million vehicles annually. This will catalyze a decisively urban shift in AV evolution as Chinese producers gear up to meet demand in areas of much higher population density, lower price points, and potentially much more restrictive energy regimes. India is also likely to be a major market. Much like today, vehicles produced for domestic use in these countries will be widely exported throughout Asia and Africa.

Ripple effects from true globalization of AV manufacturing could reach much further than emerging markets, however. Shared mobility services in many cities could suffer as producers flood the market with cheap, bare-bones private AVs. Alternately, public transit might get a boost from innovation in low-cost AV buses and jitneys takes off.

FIG. 10 AV Sales Kickoff in the Americas and Europe Before Spreading to Asia

Total Sales by Volume of Units



Market penetration by %	2020	2025	2030	2035
Americas	.010%	1.1%	5.4%	--
Europe, Middle East, & Africa	.000%	0.5%	3.9%	--
Asia-Pacific	.001%	0.3%	3.0%	--

Source: IHS Markit

Cities Take the Lead

Nations have been the gatekeepers on AV testing and commercialization, but urban markets will be the driving factor in how fast AV technology spreads.

Throughout the long incubation of AV technology, national governments have led the way by funding basic research, organizing pilots, and updating policy and regulation in transportation, telecommunications, and insurance. However, as the transition to AVs gets underway, cities will play a larger and more pivotal role.

First, cities are where AV buyers are. Initial AV sales are expected to follow trends in EVs, which are concentrated in and around the world's most prosperous cities and metropolitan areas. According to a forecast co-authored by McKinsey and Bloomberg New Energy Finance, some 70 percent of AVs sold in Europe and North America from 2015 to 2030 will be in dense cities and their high income suburbs. (FIG. 11)

Cities are also growing bigger than at any point in history. The world's largest megacities now represent auto markets that are larger than many countries. According to another McKinsey study on changes in the automotive industry, as a result "[c]ity type will replace country or region as the most relevant segmentation dimension that determines mobility behavior and, thus, the speed and scope of the automotive revolution." One likely strategic response from automakers is the creation of vehicle models that are designed for individual cities or city types.

As the transition to AVs gets underway, cities will play the most pivotal role.

FIG. 11 AV Sales Will Be Focused on Dense Cities and Wealthy Suburbs

Total Worldwide AV Sales, 2015–2030

	Dense cities	High-income suburbs	Low-income suburbs and rural areas
Europe and North America	**8M**	14M	9M
Rest of World	**13M**	2M	12M

Source: McKinsey and Bloomberg New Energy Finance

4. how

A snapshot of key demographic and regulatory drivers of AV adoption.

New Markets

AVs could unleash unprecedented new demand for automobile travel among three long-underserved groups: non-drivers, the elderly, and the disabled.

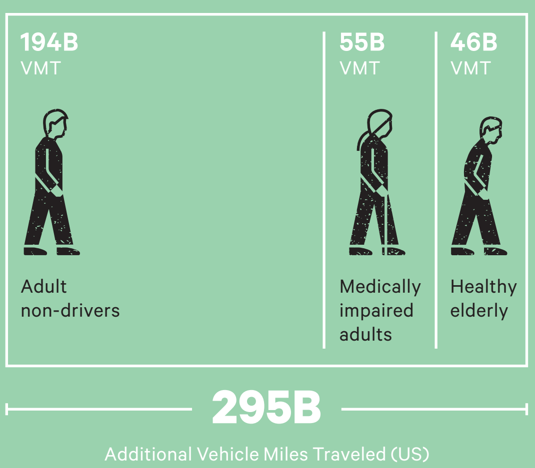
For many people, the leap from partial to fully autonomous vehicles will open doors to vastly increased mobility. The most detailed look at how these groups **(FIG. 12)** could shape future demand for AV-based travel, a 2016 Carnegie Mellon University (CMU) study, holds some startling projections. If these three groups take to AVs en masse, they could boost overall vehicle travel (in the United States) by as much as 14 percent. Add in children under 18, a tech-savvy market that mobility service startups are already tapping, and this figure could rise even higher.

Non-drivers

Many adults never learn to drive, even in highly auto-dependent nations like the United States, where licensing rates actually started declining before the advent of AVs. **(FIG. 13)** But if adult non-drivers (age 19 and over) travel by AV as much as drivers do with cars today, they could contribute some 196 billion additional annual vehicle miles traveled (VMT) in the United States, about a 4 percent overall increase.

FIG. 12 Who Will Travel More With AVs

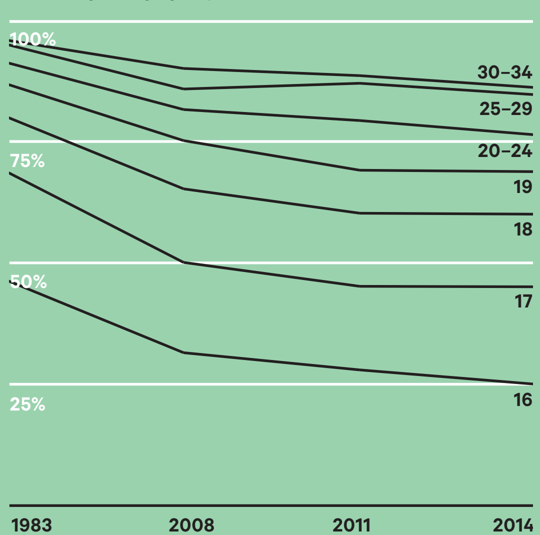
AVs will potentially grow the total VMT by 14%, totalling up to 295 billion additional VMT.



Source: Carnegie Mellon University, Department of Civil and Environmental Engineering

FIG. 13 Americans' Fading Interest in Driving

Percentage of age group licensed



Source: University of Michigan Transportation Research Institute

Senior Citizens

Persons age 65 and older are a second new source of demand for travel by AV. Focusing in just on the nondisabled, drving elderly, the CMU study calculated a smaller but still significant impact of about 46 billion additional VMT annually.

The elderly population in most developed countries with cities participating in the Bloomberg Aspen Initiative on Cities and Autonomous Vehicles will experience an historic expansion during exactly the same period (2020–2040) as the AV transition shifts into high gear. **(FIG. 14)**

The Disabled

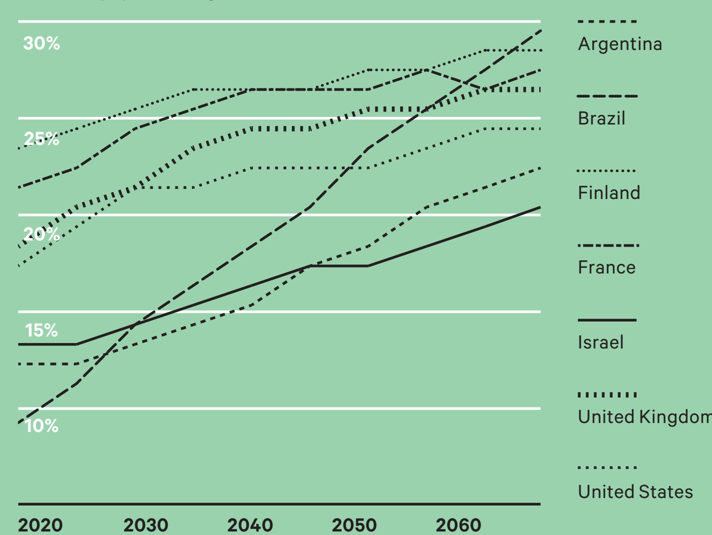
A third new market for AV-based mobility is adults over the age of 19 with temporary or permanent medical conditions or disabilities that make it difficult to travel outside the home.

The CMU study found that this group, while much smaller than the healthy elderly population, would have an even greater impact on travel demand, more than 55 billion VMT annually.

The leap from partial to fully autonomous vehicles will open doors to vastly increased mobility.

FIG. 14 Populations Are Aging Rapidly During the AV Transition

% of total population age 65 and over



Source: UN World Population Division

Consumer Attitudes

Big gaps exist between automakers' expectations and consumers' perception about the appeal of AVs. These limits will shape future products and services offered in cities.

The very young, the very old, and the disabled will face an easy choice between AVs and isolation. But how will broader consumer markets react to giving up control of the wheel? When will human drivers go the way of the elevator attendant?

Consumers Remain Skeptical of AVs

The outlook is far more uncertain than current hype would suggest. For instance, the London School of Economics conducted a massive 12,000-person survey spanning 11 European countries in 2010. Researchers found 44 percent of respondents were uncomfortable using an AV, with just 1 in 4 saying they were comfortable. They were only slightly more receptive to sharing the road with AVs. **(FIG. 15)**

Other surveys probed these feelings more closely. A 2014 survey in Germany found that people were far more welcoming to automation of individual features such as speed control and braking, but they were highly resistant to ceding control of steering or full automation. **(FIG. 16)**

Will High AV Costs Boost Sharing?

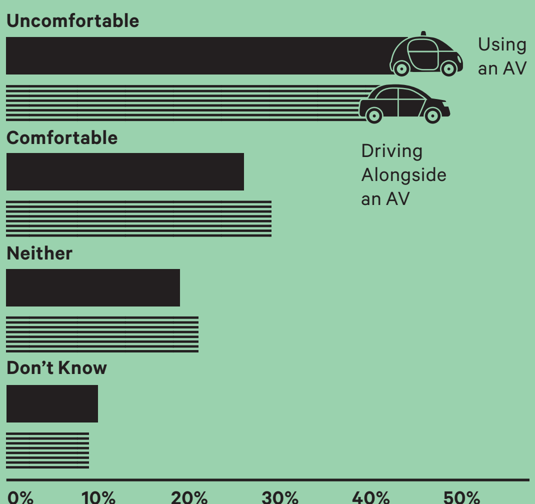
Consumers are also very sensitive to the price of AVs. A 2014 BCG survey of 1,500 Americans found that only half were willing to pay extra for self-driving features, and only 1 in 6 would pay more than $5,000.

Could shared AVs exploit this gap by appealing to the pocketbooks of urban commuters before AV prices fall? Surveys suggest shared AV services could tap into existing positive sentiment toward sharing.

Attitudes toward sharing vary considerably by age and world region. But they are highest among those age 21–34 (the so-called "millennial" generation), who will be the most important target market for AV products in the 2020s and 2030s as they age. Sharing is especially appealing to young people in the world's most rapidly urbanizing regions. Rates of acceptance for shared products and services in Asia Pacific, and Middle East and Africa—where the bulk of the world's future city dwellers will live—are more than double levels in Europe and North America. **(FIG. 17)**

FIG. 15 Are Europeans Wary of AVs?

The majority of 11,827 individuals asked about driving in or next to an AV were uncomfortable or undecided.

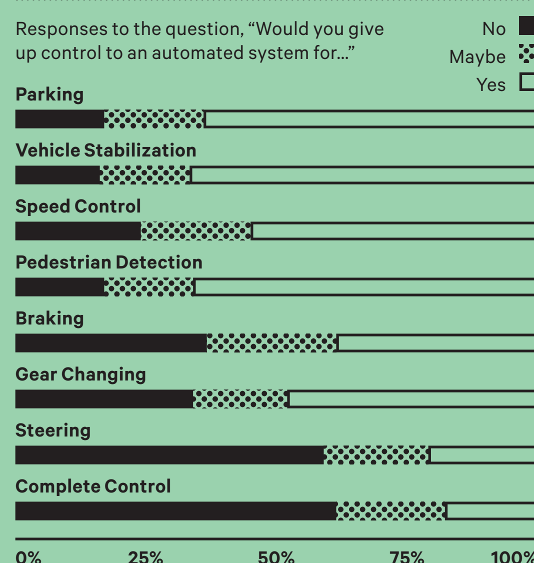


Source: London School of Economics

> "Could driving your own car become as socially frowned on as other risky habits, like smoking?"
>
> Andrew Maynard, Risk Innovation Lab, Arizona State University

FIG. 16 Drivers Reluctant to Give Up Control

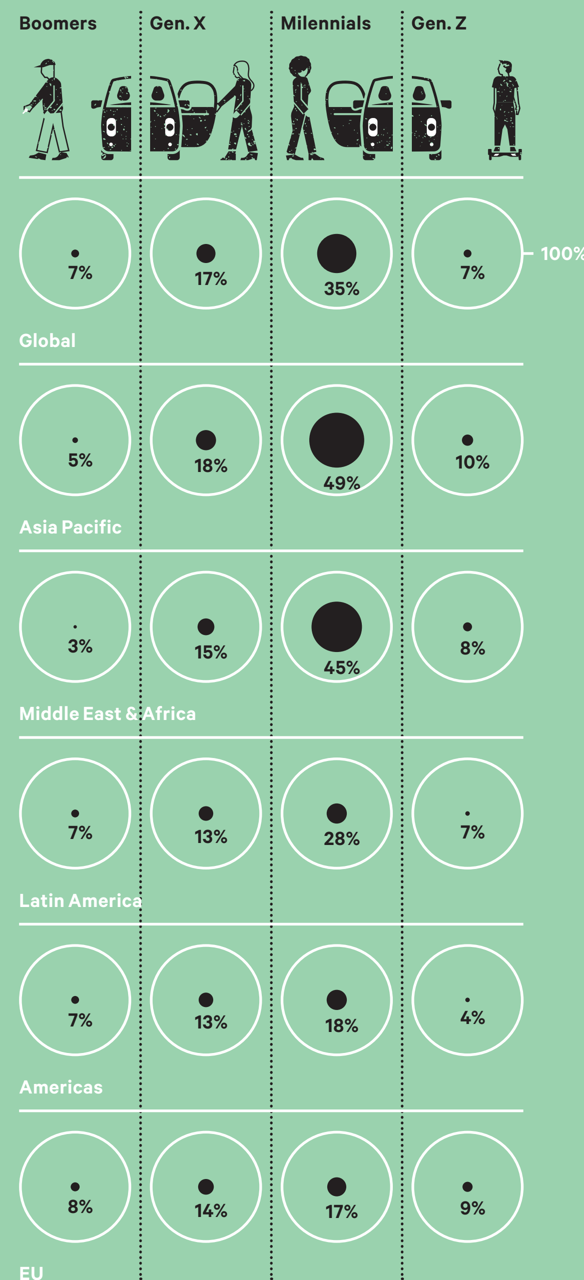
Responses to the question, "Would you give up control to an automated system for..."



Source: Ingo Wolf, Free University of Berlin

FIG. 17 Sharing Appeals to Milennials

Indicates percentage of persons in each group in the indicated region who express willingness to use or rent products and services from a shared community.



Source: Nielsen

Fleet Conversion

A variety of purpose-built AVs could take over city streets long before private cars even hit the market.

Commercial and government vehicles are a major presence on city streets, accounting for more than 25 percent of traffic. **(FIG. 18)** Building on decades of investment in navigation, communication, safety, and diagnostics technology, the road is clear for widespread conversion of urban vehicle fleets to autonomous driving in the coming years.

Trucks, Taxis, and Transit

Long-haul trucks will likely be the first widely automated fleets. Even without the elimination of labor costs, the case for automated trucking is being made on fuel savings alone. Truck platooning, a technology for closely-spaced, high-speed travel, has been shown to produce 7–15 percent fuel savings. At first, the impact on cities will be limited to urban expressways and industrial zones. But over time, the footprint of automated truck fleets will expand into more congested parts of cities.

Taxis are also on a fast track to full automation, and this will have a much greater impact on employment and city streets. Analysts at Barclays estimate that by eliminating the cost of taxi drivers' labor, full automation could slash uberPOOL's current fares for shared rides ($1.00 to $1.50 per mile) to just eight cents per mile. If even a small portion of these fare reductions is achieved in practice, use of shared AV taxis could grow rapidly.

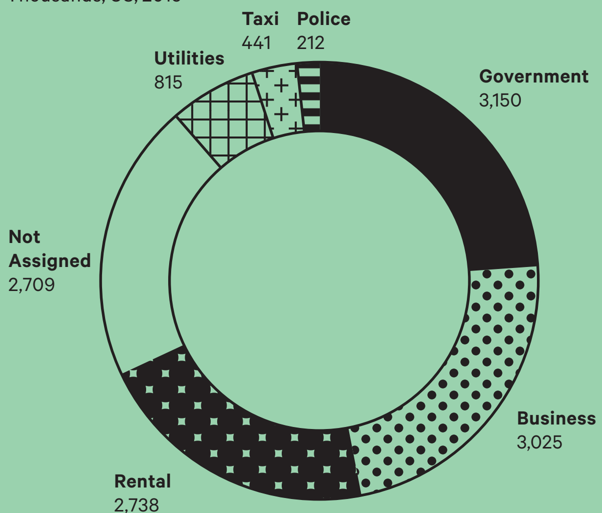
Public transit has a long history of automation, where it has been pursued to improve safety and capacity. Future investments, however, are more likely to focus on controlling labor costs as well. According to a 2015 survey of 23 metro systems worldwide, fully automated trains and fare gates can achieve a 70 percent reduction in staffing needs. For buses, where one driver is needed to transport only a few dozen passengers, driverless vehicles could reap enormous savings. The public, however, may resist such moves vigorously. When former London Mayor Boris Johnson proposed automating the city's buses in a 2014 white paper, he was severely criticized.

Gradual Upgrades for Government Vehicles

Commercial and government fleets will be automated at very different rates. Commercial vehicles in the United States average about 26,000 miles annually and are replaced every 3 or 4 years. **(FIG. 19)** In comparison, the average private car in the United States is more than ten years old. But government fleets are the slowest of all to be replaced, as they are subject to much longer working lifetimes and are replaced subject to planning and capital investment cycles. The US Postal Service, for instance, is currently testing prototypes to replace some 142,000 long-life vehicles first put into service in 1987, some three decades ago.

FIG. 18 Fleet Vehicles in Service

Thousands, US, 2015

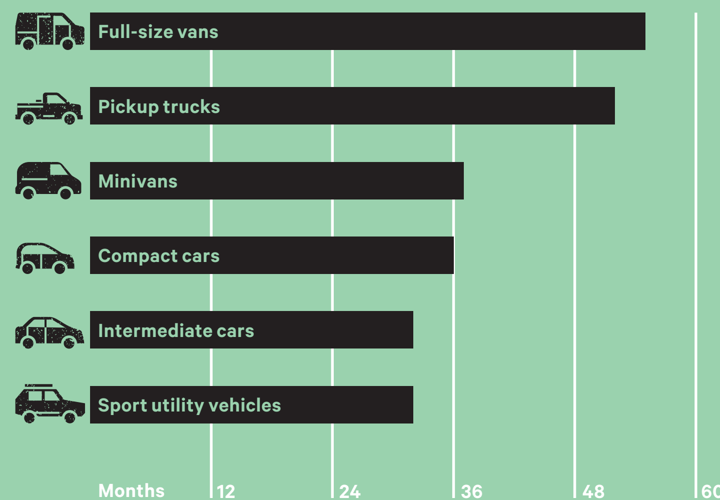


Source: US DOT, Federal Highway Administration

The road is clear for widespread conversion of urban vehicle fleets to autonomous driving in the coming years.

FIG. 19 Commercial Fleet Turnover Will Speed the AV Transition

Replacement rate for fleet vehicles (United States)



Source: Transportation Energy Data Book, Oak Ridge National Labs

Policy and Regulation

Legislatures the world over are clearing the road for AV testing and leaving the details to transportation safety officials. But holistic approaches to integrating AVs into the economy and society are lacking.

Many AV developers have sought out test sites on military bases, gated communities, and other self-governed districts where less strict rules on road use apply. For instance, Singapore's 2.5 square mile one-north tech campus hosts a number of AV pilots. But beyond such "autonomous zones," the process of formulating AV policy has been haphazard.

The most decisive policy-making action on AVs in the last five years has been taken by US states, which face intense lobbying efforts and competition for industry investment and jobs. These regulations authorize testing of AVs on public roads but are considered by many legal experts to be symbolic and largely unnecessary. AV testing legislation has now been introduced in 35 of the 50 states and adopted in six. **(FIG. 20)**

National Policies

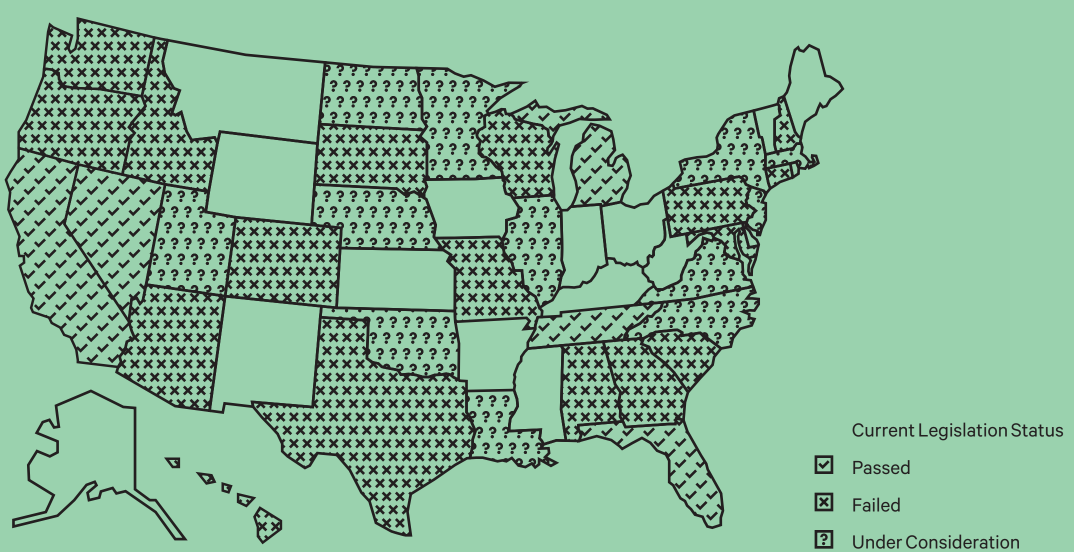
Cities around the world are tightly constrained by national policy on AVs. But action has been sporadic and not particularly sensitive to cities' concerns.

In the United States, for instance, transportation regulators issued a landmark set of AV testing policy guidelines covering safety, reliability, data standards, and privacy. While directed at state governments, the report mentioned cities exactly twice in 116 pages.

Other nations are assessing and reforming existing laws that apply to AVs. A key issue has been the legacy of the 1968 Vienna Convention on Road Traffic. The treaty, which established international standards for traffic rules, states that "every driver shall at all times be able to control his vehicle." The treaty was updated in 2016 but still requires human operated fallback modes. The control-free AV interiors proposed by Google would still not be permitted.

Many nations face bigger structural obstacles in the AV transition. In a September 2016 white paper, the Brookings Institution identified key policy challenges facing a number of countries and the EU. These focus on setting clear jurisdiction between agencies, updating data protection rules, and reforming insurance markets. **(FIG. 21)**

FIG. 20 Two-Thirds of US States Have Considered or Adopted AV Laws



Source: Stanford University, Center for Internet and Society

Cities Explore the Issues

Cities are only just beginning to regulate AV testing. A small but growing number of planning efforts, however, are looking at the long term opportunities and needs. In 2015, just four of 68 major US cities surveyed by the National League of Cities in 2015 addressed AVs in their long-range transportation plans. Among metropolitan planning organizations (MPOs), the regional bodies that direct federal transportation funds at the state and local level, just one in 25 plans mentioned AVs. By 2017, however, five more of these had been updated to mention AVs.

Cities' recent battles with transportation network companies (TNCs) like Uber suggest that local AV regulation could take shape in conflict with industry. However, more collaborative processes are possible too.

Cities around the world are tighly constrained by national policy on AVs.

FIG. 21 National AV Policy Challenges

Country	Key AV Regulatory Needs
China	Clarify ministerial jurisdiction and regulatory mechanisms
	Invest in AV highway infrastructure
	Eliminate prohibitions on road testing
	Loosen restrictions on road map development
Europe	Strengthening AI industry for technological competitiveness
	Revise data protection rules to reduce obstacles to precise location tracking for AV applications
Japan & Korea	Invest in AI, mapping and analytics R&D and education
U.S.	Clarification of liability and data privacy rules
	Criminalization of AV-related cyberattacks/ hacks

Source: The Brookings Institution

Lyft and many smaller TNCs have sought to work closely with cities and transit agencies. Increasingly, the focus of cities' regulatory efforts will focus on the virtual operations of these companies and securing the needed data on trips, fares, and wages to ensure safety, efficiency, and fairness.

Policy networks are taking shape quickly as stakeholders move to inform and influence debates at all levels of government. In the United States, AV makers and service providers formed the Self-Driving Coalition for Safer Streets in April 2016 to coordinate industry's lobbying efforts. Members include Uber, Lyft, Ford, Waymo (Alphabet), and Volvo. The National Association of City Transportation Officials (NACTO), a coordinating body comprised of officials from large American cities, published a set of nine guiding principles for its members in June 2016. **(FIG. 22)**

> "Autonomous vehicles offer a once-in-a-lifetime opportunity to reset our streets and address the fundamental issues of traffic safety, congestion, and mobility as our cities grow ever larger."

Janette Sadik-Khan, transportation principal at Bloomberg Associates and NACTO Chair

FIG. 22 NACTO's Principles for Future AVs

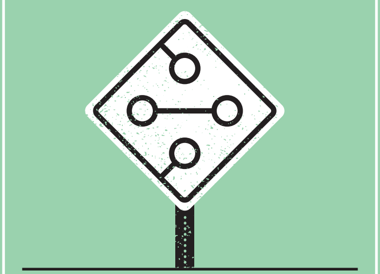
Safety

Plan for fully automated operation (NHTSA Level 4) to support Vision Zero.

Regulators and product designers should bar the use of partially automated vehicles (NHTSA Level 3) on any roadway without controlled access, like city streets.

Maximum operating speed in a city street environment should not exceed 25 miles per hour.

Modernization



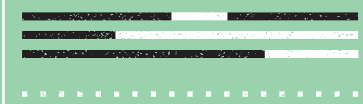
Modernize plans for expressways, pivoting from expansion to modernization and management.

Transportation planning at all levels should refocus on modernizing existing expressways with instrumentation for new technology.

Funding

Policies at the Federal and State levels for infrastructure funding must be revised to reflect the restructuring of the transportation system

Planning



Include transportation professionals from cities.

Future visioning for automated vehicles should begin from the inside out, from the centers of our economy, looking at land use as well as transportation.

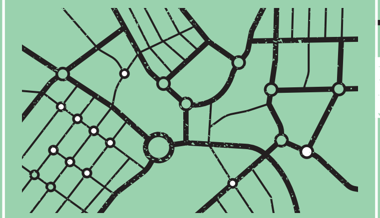
Research

Federally and state supported research on automated vehicles should focus on city street operations of shared, automated, electric vehicles.

Increased Federal and State funding for city operation of automated vehicles. Research should address any needs for on-street infrastructure in the city environment and how to cover those costs.

The future of transit vehicles and their unique needs in terms of automation should be investigated to ensure transit can benefit from advances in technology.

Modeling

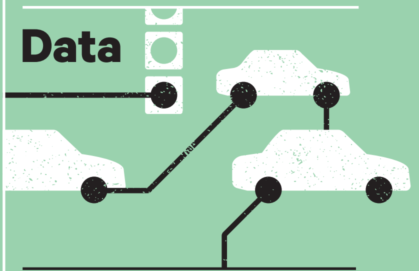


Adjust and standardize lower travel time costs beginning with model year 2020.

Beginning as soon as model year 2020, per-minute travel time costs could be an estimated 80 percent lower.

To support this change in modeling, a metropolitan modelling exercise for North America similar to the Lisbon model released by the International Transport Forum in 2015 would be beneficial in understanding how this shift in transportation costs may affect overall travel patterns.

Data



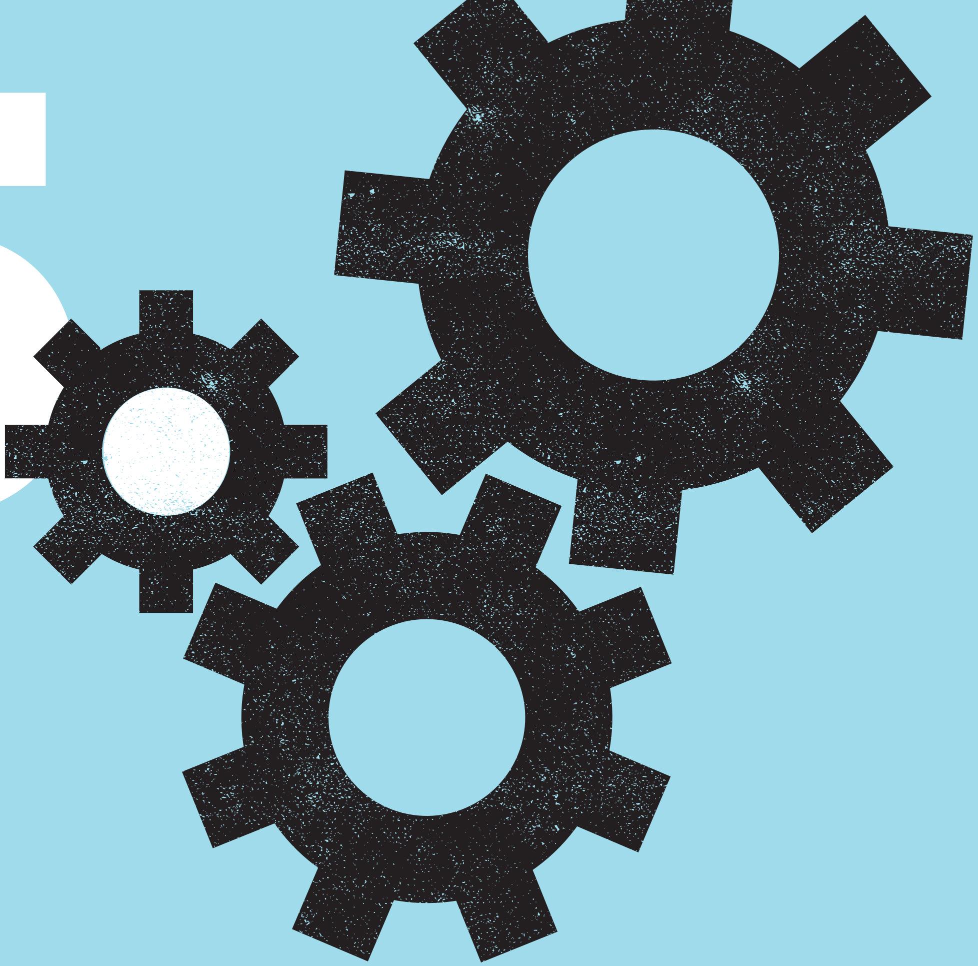
Develop and implement robust data-sharing requirements for new vehicle technology.

Freight

Support safer, more efficient, environmentally sustainable freight systems.

Source: National Association of City Transportation Officials

5



who

A portfolio of movers and shakers in the emerging AV industry.

Driving Disruption in Silicon Valley

In the last decade, Silicon Valley's cultural heart has shifted to San Francisco. Now a new generation of city-loving tech tycoons think that technology can solve urban problems.

Many in Silicon Valley see AVs as the future of the internet, and a massive business in their own right. **(FIG. 23)** There's also a sense that the know-how gained in building global networks for electronic commerce and communication can be retooled to re-engineer urban transportation systems from the ground up. How are the likes of Google, Apple, and Amazon taking on this challenge? We see three basic strategies at work: full automation, coordination, and consumer transformation.

Full Automation

Rather than incrementally adding partial autonomous driving features, in 2009 Google set out to develop a fully autonomous vehicle from scratch. Google's approach was the strongest signal yet that the tech industry's aggressive pursuit of full driving automation will be focused on autonomous operation, without the need for any changes to the existing road network. This strategy seems primarily aimed at fleet operators—taxis, transit, and trucks.

Coordination

A second strategy focuses on automating entire transportation systems rather than individual vehicles. This approach also makes extensive use of AI to manage highly complex flows of vehicles, passengers, and goods. Both Google and Amazon are also developing multiple types of AVs for moving passengers and freight. As these globe-spanning visions mature, the urban implications are becoming clearer. Amazon, for instance, recently patented a design for massive airborne distribution hubs that that could float over stadiums or urban neighborhoods during the holiday shopping season. **(FIG. 24)**

Consumer Transformation

Tesla represents a third strategy, focused solely on consumers.

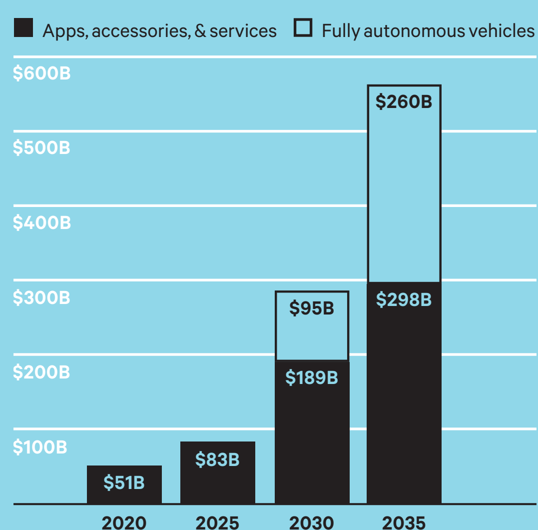
By embracing the latest technologies, electric drive and partially autonomous driving, the company has created highly distinctive products in the existing automotive markets. Like Apple's disruptive entry into the music business 15 years earlier, the company has simultaneously appealed to current consumer desires while also introducing technologies that have both new capabilties and constraints.

These new technologies are changing the way the company does business in ways that create new opportunities and challenges for cities. Tesla routinely releases unannounced over-the-air software updates to existing vehicles. For instance, in October 2016, which

> "If enough people see the machine you won't have to convince them to architect cities around it. It'll just happen."

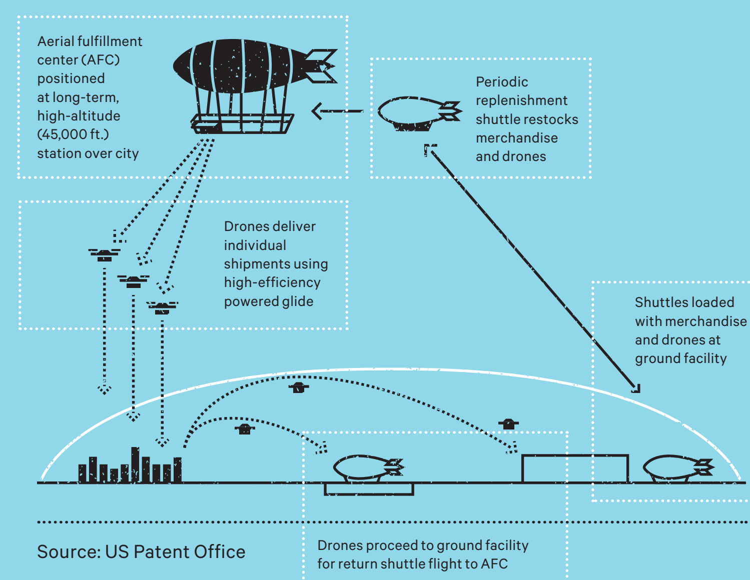
Steve Jobs, on the transformative potential of the Segway scooter (2001)

FIG. 23 Software will be a Big AV Business



Source: A.T. Kearney

FIG. 24 Amazon's Vision for Airship-Based Logistics



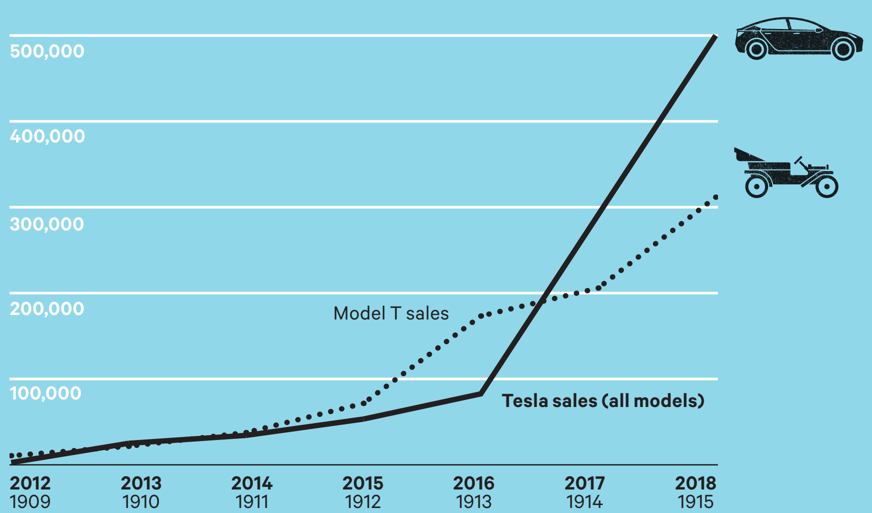
Source: US Patent Office

instantly upgraded the company's entire fleet with a variety of Level 2 self-driving capabilities dubbed Autopilot. Cities may find themselves scrambling to keep up with sudden changes in AV operation triggered by these changes. But the company's focus on incremental improvement through code has allowed it to get more AVs on the road than any other company. These "test" vehicles are gathering an unmatched set of data to improve product design, a vast potential source of information for cities interested in traffic safety, road conditions, and changes to the built environment.

Who Will Shape the Future of Urban Transportation?

For now, it's unclear which strategy will reap the greatest rewards for investors, and for cities. The tech giants continue to jostle for position. Google was the first tech company to jump into AVs, but now appears to be the first to jump out. In late 2016, the search giant spun off its AV efforts into Waymo, which will move ahead under a more traditional partnership with automaker Fiat Chrysler. Tesla may be trying to create a latter-day version of the traction monopolies, conglomerates that controlled both the production of electric power and the urban streetcar systems that were its main consumers. The company's success has spurred its leadership to push the company onto a targeted expansion that would move it ahead of where even Henry Ford's Model T was at a similar stage of development. **(FIG. 25)** Uber may be banking on a future where surface transportation becomes more like air travel, with consumer loyalty shifting from vehicle manufacturers to carriers. Apple looked ready to make an AV play positioned as an extension of the digital home, secretly assembling a team in 2015, only to second-guess itself and pump $1 billion into Chinese ride-source giant DiDi instead.

FIG. 25 Tesla's Forecast Would Surpass Ford's Early Success



Source: Bloomberg News

"There's an urgency to our mission about being part of the future. This is not a side project. This is existential for us."

Uber CEO Travis Kalanick, on deploying AVs in Pittsburgh

The Auto Industry Retools

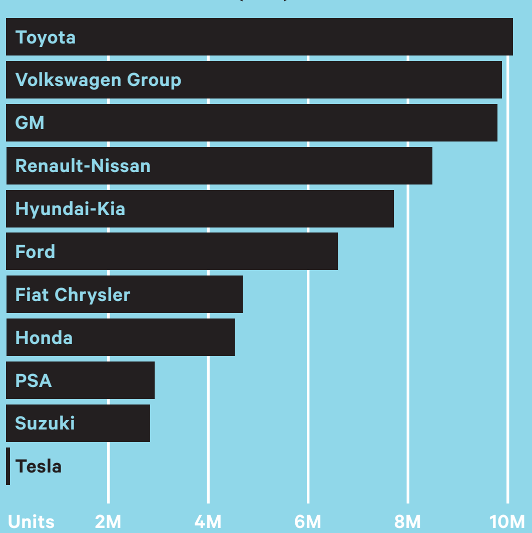
Automakers are bouncing back quickly from the tech world's sneak attack. But can the industry use the AV transition to overcome its anti-urban legacy?

In the 20th century, car companies worked for decades to turn the public against cities and public transportation. Those mistakes are mostly in the past, and many automakers are trying to find a new role in sustainable urban mobility that's less focused on selling cars to consumers.

AVs are a key to making this shift. Reeling from the tech industry's media blitz in 2015 and 2016, automakers have retooled and expanded long-simmering AV research and development programs. In the coming decade, these programs are expected to push a wide variety of partially and fully autonomous vehicles to market.

FIG. 26 Global Automakers' Scale Advantage

Annual Vehicle Production (2015)



Source: Forbes

Existing car companies will have a built-in scale advantage to help fend off the tech industry's challenge. Today, Volkswagen and Toyota each produce nearly 10 million passenger cars each year. Tesla would have to double its meager production—just over 75,000 cars in 2016—every year for a decade to reach an equivalent level of production. **(FIG. 26)**

A Flurry of Investments

Big automakers have gone on a spending spree to boost their tech credentials. A growing flurry of investments, acquisitions, and alliances has gained momentum in the last year. **(FIG. 27)**

US automakers are most exposed to the technology giants' advances. General Motors invested $500 million in Lyft in 2016, a deal the automaker described as an "alliance." The move sets up GM as the ride-share pioneer's future supplier of AV taxis. Ford, an early investor in Lyft, doubled the size of its Silicon Valley office.

Outside the United States, European and Asian carmakers are also heavily investing in AVs. Volvo, will begin the world's first full-scale consumer pilot in Gothenburg in 2017. Fiat Chrysler flirted with Apple before partnering with Google in the Waymo spin-off.

Japan: A Sleeping Giant Awakes in 2020?

Japanese automakers have lagged badly behind their US and European counterparts in the development of AV technology. According to Bloomberg Technology, most do not expect to market AVs until 2025, considerably later than US and European counterparts.

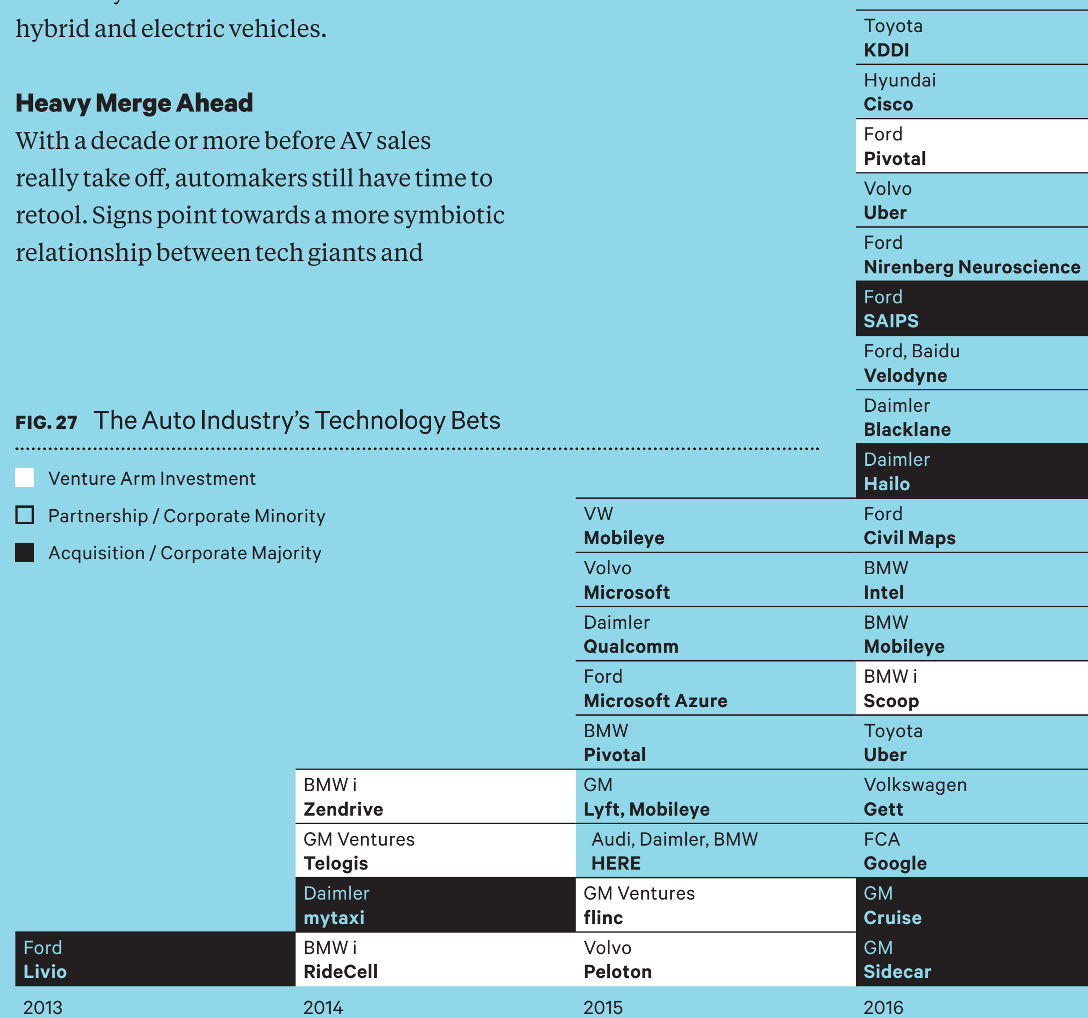
The 2020 Toyko Summer Games could be a landmark event for urban AVs, situated in the world's largest megacity in the most robot-friendly country. Japan has long been the world leader in robotics and industrial automation—with more industrial robots in use than the US and Germany combined. The Japanese government is pushing hard to exploit the opportunity, hoping to pull off a major demonstration of AV taxis to transport athletes. The event could prove catalytic for Japanese industry and have impacts that shape the urban AV market as profoundly as the Toyota Prius and Nissan Leaf did for hybrid and electric vehicles.

Heavy Merge Ahead

With a decade or more before AV sales really take off, automakers still have time to retool. Signs point towards a more symbiotic relationship between tech giants and carmakers, rather than head-on competition (Tesla excluded).

But will the marriage of Silicon Valley and the auto industry last? A September 2016 *Fortune* feature on the GM-Cruise deal suggests rough patches ahead, noting that Cruise co-founders "Vogt and Kan are being pulled into more tedious corporate meetings, where committees of executives are required to sign off on decisions and budgets that they're used to handling themselves."

FIG. 27 The Auto Industry's Technology Bets

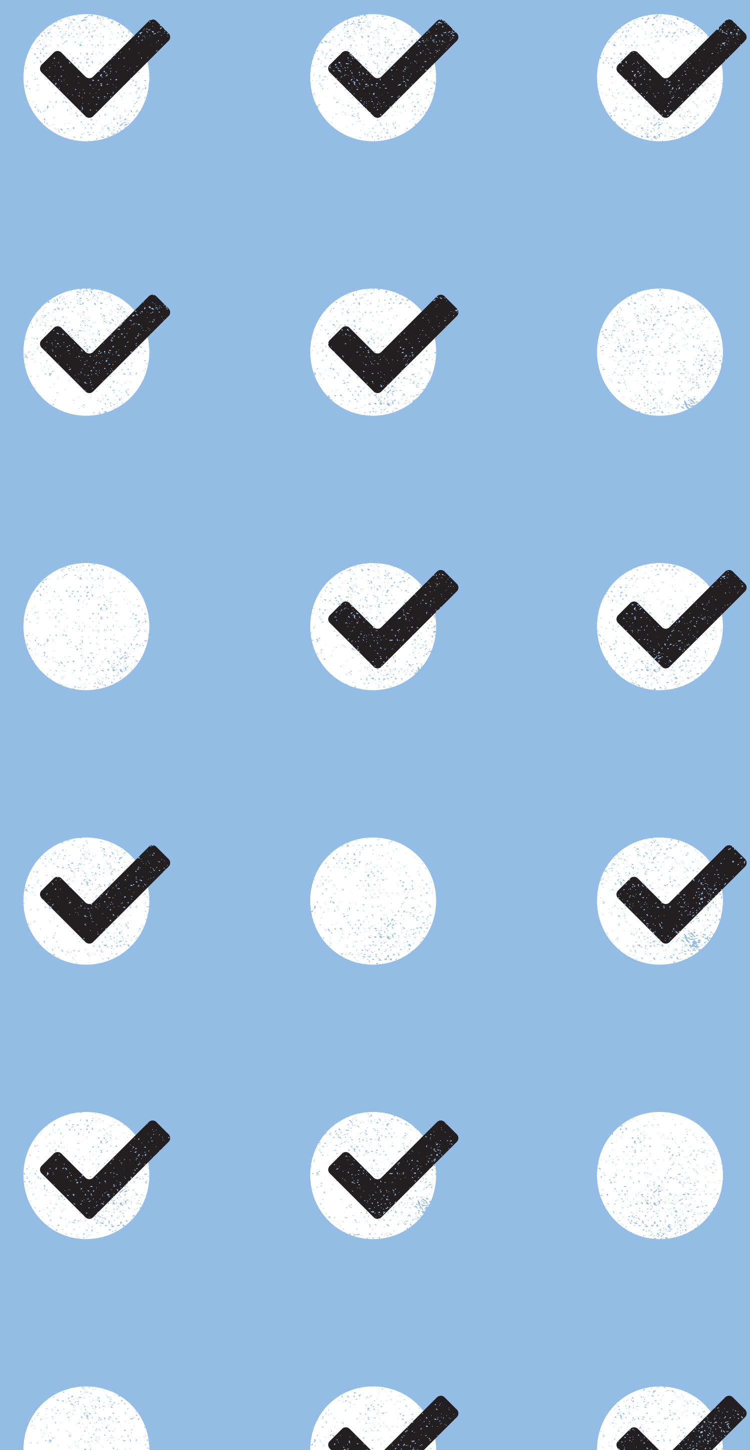


Source: CB Insights

6

why

A scorecard of benefits, risks, and unintended consequences of AVs.



The Urban Dividend

Cities could see a wide range of benefits as the AV transition unfolds. AVs could also present a range of anticipated and unanticipated challenges. Much more research is needed before these opportunities and challenges can be fully mapped.

AVs are fast becoming a go-to symbol of progress. But even as they promise to deliver safe, efficient, carefree travel, they will also provoke strong responses and heightened anxieties about the destabilizing effects of automation.

Cities will be the focal points for these hopes and fears. Cities are where AVs will arrive first, in the largest numbers and most intense concentrations. They are the ideal place for government to draw the lines that allow AVs to serve us, instead of forcing us to adapt to their many limitations.

An Initial Exploration of the Impact of AVs

This final section looks at seven areas of urban policy and planning likely to be shaped by AVs in the coming decade and beyond: traffic safety, mobility, sustainability, jobs and the economy, human services, public finance, and land use.

The scope of these explorations is severely limited by the small body of existing research on the potential impacts of AVs. This section aggregates existing studies and forecasts, but there are large gaps around issues that have not been studied.

This is not an exhaustive list, nor a complete inventory. It is provided as an illustrative sample of benefits, risks, and unintended consequences that may accompany the AV transition in cities. It is intended to kickstart cities' own assessment of where the key leverage points for shaping the future may lie. There are certainly other opportunities and challenges that we are not yet able to anticipate.

Most importantly, it seeks to show cities potential avenues to bridge the detailed work to prepare for AVs already underway in the urban transportation field with strategic thinking about broader impacts in other areas of city government.

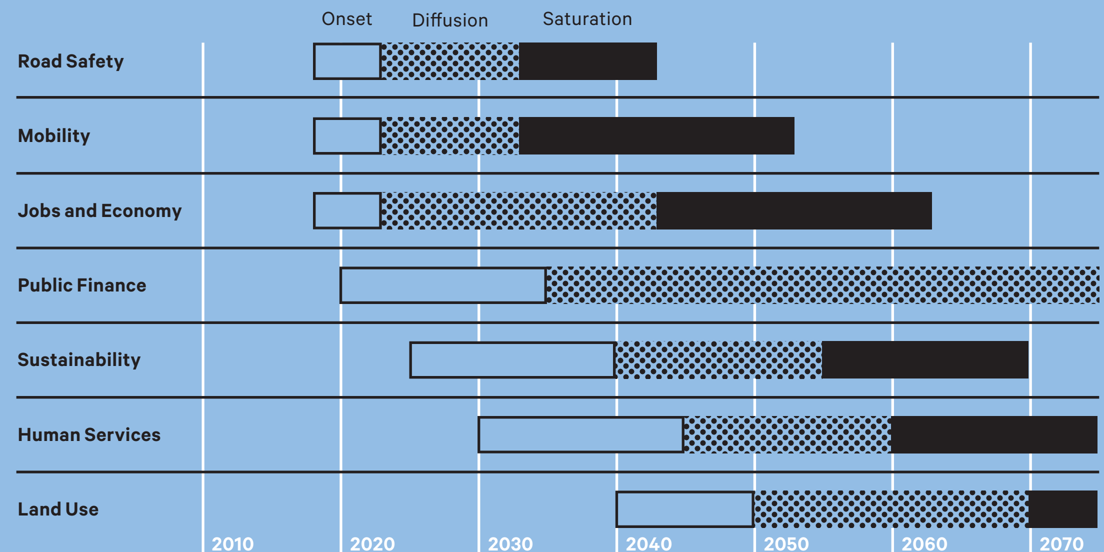
Gauging The Pace of Change

Some of the impacts of AVs will arrive sooner than others. For instance, the high standards for safety should quickly deliver tangible reductions in road accidents. In other areas, like jobs or land use, the impacts may be more subtle at first and grow over time, potentially giving cities more ability to steer outcomes. **(FIG. 28)**

> "My whole career, people have been saying: We wish we could have known the social costs of driving, we would have done this differently. Policymakers have to think about this now, because the decisions they make affect the landscape for a century."

Constantine Samaras, professor of civil and environmental engineering at Carnegie Mellon University

FIG. 28 How the Impacts of the AV Transition on Cities Could Grow Over Time



Source: Bits and Atoms

Road Safety

AV advocates are making big promises about highway safety. But how soon can AVs reduce risks on city streets, and will the costs be worth it?

Proponents see an opportunity for AVs to all but eliminate some 1.34 million road deaths the WHO estimates occur each year. But most of these fatalities occur in rapidly urbanizing countries where car ownership is booming, drivers are younger and less experienced, and unsafe vehicles are commonplace. Fully one-third of the total fatalities in 2013 occurred in China and India alone. For AVs to have a significant positive impact on road safety in low-income countries, fundamental improvements in road infrastructure, vehicle safety standards, and traffic regulation are needed.

Distracted Driving Turns the Clock Back

In wealthy nations, decades of safety gains are at risk from the recent rise in distracted driving. In the United States where this reversal has been most acute, deaths spiked more than 10 percent in 2016 **(FIG. 29)**.

Many see AVs as a panacea for distracted driving. AVs can respond to an emergency as much as six times faster. This would eliminate almost all collisions currently caused by inadequate braking.

AVs can also be programmed to try to avoid accidents, by steering around a stopped vehicle, for instance. But if an AV swerves to protect its occupant(s) by avoiding a collision, how should it weigh the increased risk that may create for nearby pedestrians, cyclists, or oncoming vehicles? Experiments like MIT's Moral Machine **(FIG. 30)** are using crowdsourced

surveys to harness humans to create ethical guidelines for AVs.

Partial Autonomy's Cloudy Future

Many safety experts see partial autonomy as a stopgap against the spike in distracted driving deaths. Studies in the United States suggest that universal adoption of existing features like blind spot monitoring, lane departure warning, and forward collision warning could eliminate hundreds of thousands of crashes a year. But these gains would largely come from highway use.

But other research shows that partial AVs will make distracted driving worse by lulling drivers into complacency. Tests at Virginia Tech found drivers took an average of 17 seconds to response to takeover requests from Level 3 AVs.

Safer City Streets?

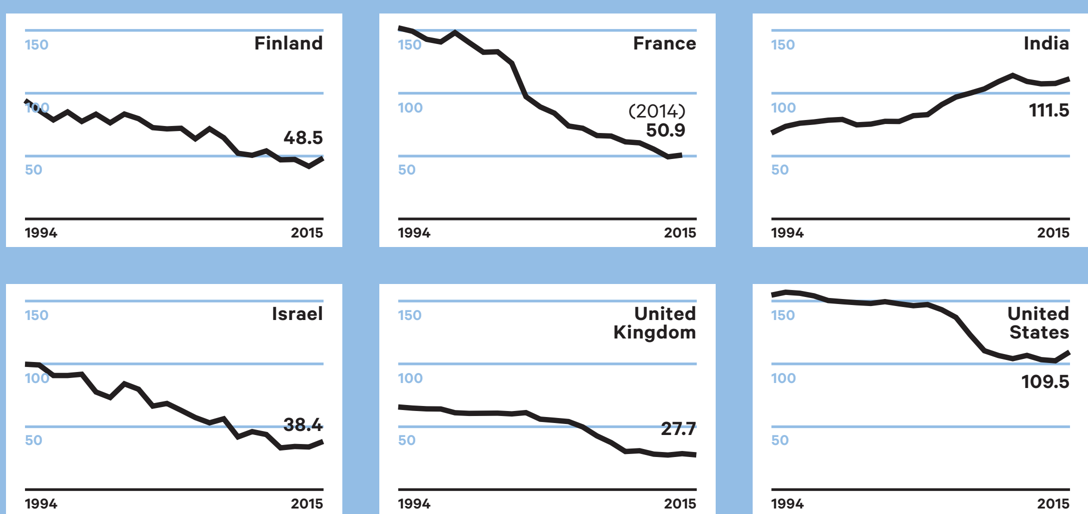
If AVs deliver promised improvements in road safety in urban areas as well as highways, they could be a boost to cities' Vision Zero campaigns to eliminate traffic fatalities. But complete automation of urban traffic is many decades away. In the meantime, anxiety over the risks of partial automation led the National Association of City Transportation Officials to recommended banning them entirely from cities.

Improving AV safety might also cause other problems. Will full AVs move so timidly they cause new kinds of traffic congestion? Will AV makers use a false confidence in AV infallibility to remove other existing safety features?

And other questions remain. What testing protocols must cities put in place? Do they have the necessary authority to do what's needed?

FIG. 29 Distracted Driving May Threaten Decades of Automotive Safety Gains

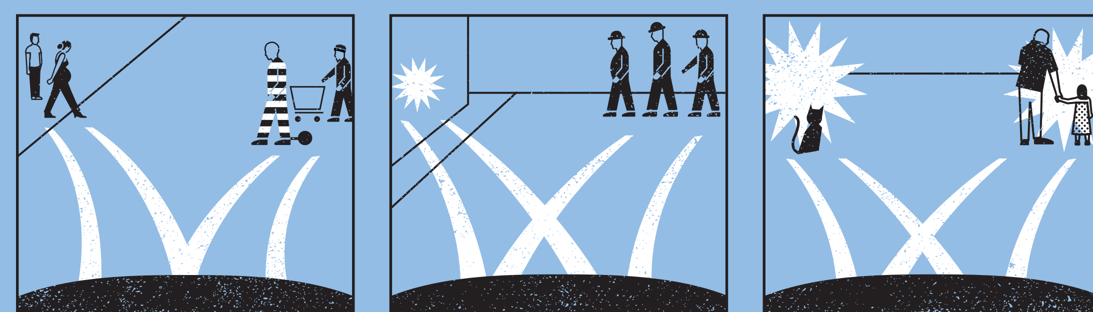
Road traffic fatalities per 1,000,000 inhabitants (1994–2015)



Source: Organization for Economic Co-operation and Development (OECD)

FIG. 30 Moral Dilemmas Abound for AVs

Shown here are three examples of the moral dilemmas that an AV may face while navigating the city. Each scenario presents A and B options—which would you choose?



A Empty car kills one pregnant woman and one man

B Empty car kills one homeless man and one male criminal

A Three male athlete passengers die in car crash

B Three male street performers killed by car

A Two adults and a cat die in car crash

B One adult and one child, both pedestrians, are killed by car

Source: MIT Media Lab

Mobility

While AVs have long promised to smooth commutes for car owners, their biggest impact on cities might be delivering cheap, pervasive public transit.

Second only to safety, high-speed highway platooning is the most widely hailed benefit of AVs. Estimates of the increased vehicle throughput highway platooning could achieve range from 250 to 500 percent. But this says little of what will happen in cities.

From Luxury to Utility

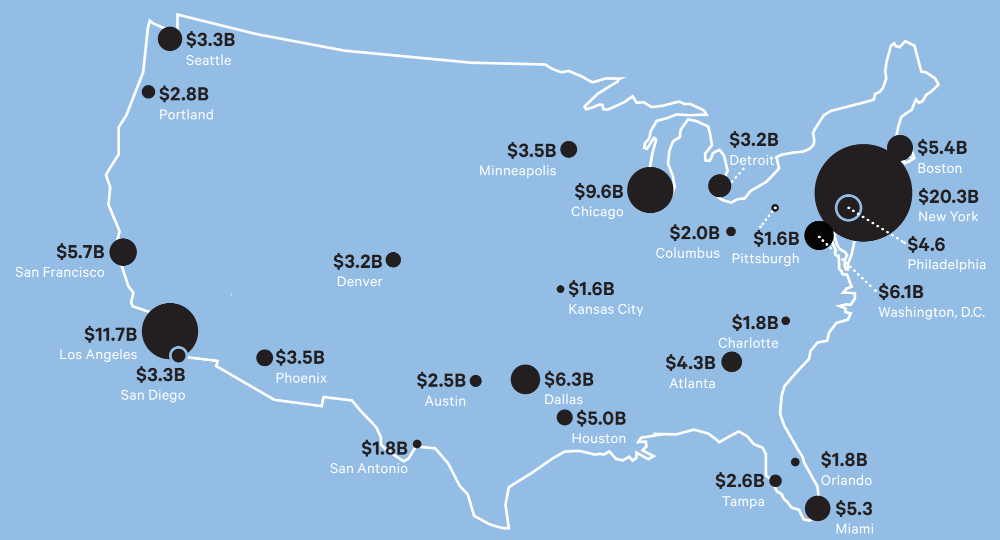
A much different future for the urban AV could be unlocked through sharing. In this scenario, shared electric AVs (dubbed 'taxibots' by the OECD) could displace most private cars from cities by 2030.

How would this work? It would depend on the creation of a virtuous cycle of falling costs and rising ridership, enabled by automation. Existing ride-share services like Lyft Line and uberPOOL have shown that a ready market exists for cheaper taxi trips. As automation drives fares for shared rides even lower, this market will expand, enticing more operators to bring more taxis online. The Rocky Mountain Institute, a sustainability think tank, estimates that at $1 per mile, automated mobility services (both shared and private ride) could be a $120 billion industry in US cities by 2025. **(FIG. 31)**

The End of Cars?

A rapid shift to taxibots—even for just some auto travel—would have a profound impact on city streets. While speculative, a scenario-planning exercise carried out for the City of Toronto in 2015 concluded that as many as 80 percent of the city's private cars might disappear by the early- to mid-2030s if such services were widely adopted. In a mixed scenario where private AVs and taxibots split the travel market, as many as 50 percent of private cars could still be eliminated.

FIG. 31 Automated Mobility Could be a $120 Billion Urban Industry in the US by 2025



Source: Rocky Mountain Institute

Boon or Bane for Transit?

Taxibots could prove to be symbiotic extensions of transit systems, much like today's ride-share services. They could provide easier and cheaper last-mile connections to rail stations, extending the value of these costly networks over a larger area. And automated buses could give new life to conventional fixed-route services.

In some situations, shared AVs could steal riders away from transit with door-to-door services. Careful oversight, gleaned from actual trip data, will be needed to ensure equitable access for disadvantaged groups and underserved areas. It's also unclear how much these services can be extended into less densely populated and outlying areas, even as operating costs fall.

Key questions remain. How far should cities go to incentivize shared AV services? Should transit agencies operate their own AV-based services? What kinds of data should taxibot operators share for traffic safety, taxation, and transportation planning purposes?

> "Building a car that can drive everywhere is very challenging.... It is more promising to start with a different goal: a shuttle/bus that can only drive one bus route or just in a small region."

Andrew Ng, chief scientist, Baidu

Sustainability

The AV transition will improve vehicle efficiency and accelerate the shift to clean energy. But these gains could be wasted if precautions are not taken to manage a potential surge in travel.

AV platoons could do more than just smooth the flow of traffic. They could deliver enormous energy savings. In 2016, the European Truck Platooning Challenge demonstrated that platoons involving just two trucks could result in fuel savings of up to 15 percent for long highway trips. Transportation consumes 50 percent of fossil fuels and produces 50 percent of emissions in developed economies. AV-related reductions in both could quickly add up.

For cities, however, there are more important environmental gains to be had from AVs. According to a 2014 analysis by the US National Renewable Energy Laboratory, several other advantages—accelerated adoption of electric vehicles, reduction in vehicle weight, smoothing of peak demands for electricity, higher occupancy, and more efficient driving—will all make a greater positive contribution to energy demand than platooning alone. **(FIG. 32)**

Electrification

The acceleration of vehicle electrification is by far the most significant positive impact of AVs on energy use. As the NREL researchers note, automation is easier with electric driveline (the parts that deliver power from the engine and transmission to the wheels). It can improve docking operations for both wired and wireless recharging mechanisms.

Transportation consumes 50 percent of fossil fuels and produces 50 percent of emissions in developed economies. AV-related reductions in both areas could quickly add up.

Finally, automation can greatly reduce range anxiety by locating, planning, and even moving automatically to charging points.

Smaller and Lighter

The federal study also highlights how combined AV/EVs could be significantly lighter, a significant source of savings. This would come about in two ways.

The first, which would be realized immediately, would be right-sizing vehicles for trips. While today, many large vehicles often carry single occupants, shared AV fleets could feature a variety of smaller vehicles. According to a 2015 study at Lawrence Berkeley National Laboratory, half the reduction in greenhouse gas emissions of taxibot systems would come simply from using smaller vehicles.

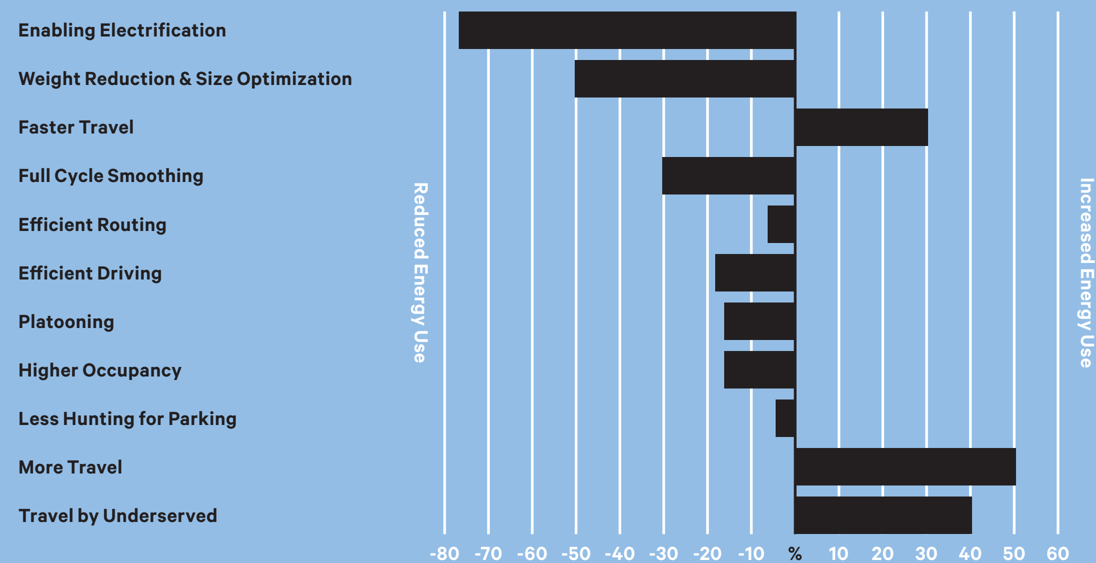
A second source of emissions reductions could come as AVs substantially eliminate the threat of collisions. By 2050, reduced structural frames could drive vehicle weight reductions of 30 to 40 percent, according to the National Research Council.

Higher Occupancy Through Sharing

A third major source of emissions reductions is higher occupancy, achieved through shared AV taxis.

But just how realistic are these expectations around shared AV taxis? Since 2013, at least five major studies have sought to demonstrate the potential gains from shared AVs in a handful of cities, including New York, Singapore, Lisbon, and Austin. While these studies differ significantly in assumptions and methods, they consistently show that automation can

FIG. 32 AVs will Unlock Many Shifts in Vehicle Energy Consumption



Source: National Renewable Energy Laboratory reduce the size of taxi fleets, and AV ride-sharing is likely to substantially reduce the need for private vehicle ownership. The latest simulation (which coined the term taxibot) found that, when deployed alongside fixed-route mass transit networks, shared-ride AV taxis could all but eliminate the convenience advantage of personal autos. **(FIG. 33)**

Transit is Still Essential

These studies have fueled excitement around the potential for urban taxibot systems. But shared AVs are not without risks for cities' sustainability efforts. Without a core of fixed-route mass transit, shared AV networks will actually lead to more VMT, not less regardless of how many cars are taken off city streets. The taxibots in the Lisbon model, for instance, actually end up driving 6 percent more miles than the current fleet of private vehicles and taxis as they make empty trips to reposition between passengers. And this is the best-case scenario, assuming that the city's transit system stays in place. When the researchers deleted public transit from the shared-ride flavor of the simulation, VMT surged 22 percent over the current baseline. In extreme cases, AVs could also become so cheap and convenient that they compete head-on with walking and cycling for short-distance trips. They might also overwhelm complete street designs with unpredictable and spontaneous traffic loads.

AVs could become so cheap and convenient that they compete head-on with walking and cycling for short-distance trips.

FIG. 33 Major Simulation Studies All Point to Big Benefits from Shared AVs

City	Year Published	Research Organization	Methods and Findings
New York City	2017	MIT, Computer Science and Artificial Intelligence Laboratory	In a simulation based on 3 million yellow cab trip logs, researchers found 3,000 shared AVs carrying up to 4 passengers could meet 98% of existing taxi demand within an average wait time of 2.8 minutes and an average additional trip delay of 3.5 minutes.
Lisbon	2015	OECD, International Transport Forum	With existing transit left in place, a shared AV taxi system would result in just a 6 percent increase in total miles travelled, but eliminate 90 percent of vehicles citywide. Reclaimed roads and parking could provide significant environmental benefits.
Austin	2015	University of Texas, Center for Transportation Research	This advanced simulation (based on the leading MATSim agent-based engine) focused on a shared AV network in a 12-mile by 24-mile area in Austin's regional core, finding that private ownership could be replaced with a fleet just 10 percent the size. An 8 percent increase in vehicle travel, however, would result from repositioning of AVs.
Singapore	2014	Singapore-MIT Alliance in Research and Technology	This study modeled a city-wide shared AV taxi system replacing all private autos and public transit, and found that all current mobility needs could be fulfilled with one third the number of vehicles currently operating in Singapore.
New York City	2013	Columbia University, The Earth Institute	Using aggregate taxi system data, this model concluded that a conventional non-shared AV taxi system could provide on-demand rides at a cost of 90 percent below current fares, reduce taxi fleet size from more than 13,000 to 9,000 vehicles, and cut wait times from an average of 5 minutes to under 1 minute.

Source: Various

Jobs and the Economy

Fears are mounting about automation's impact on work and jobs. But AVs could be an essential catalyst for urban economic growth and innovation.

In 2016, the average American driver commuted more than 24 minutes each way, up 20 percent since 1980—a stunning 29.6 billion person-hours of lost time each year, according to the US Census. The Texas Transportation Institute estimates this lost productivity at $160 billion per year in the United States alone.

A Rough Road for Rolling Offices

Numbers like these will be powerful ammunition for future AV marketers, given the high incomes of likely early adopters of AVs. But will people actually spend their AV commute time productively? A 2014 poll of 1,000 Germans strongly indicated that people would prefer to do almost anything except work. Among seven different in-car activities, "working during the journey" ranked nearly last, just ahead of watching movies. **(FIG. 34)**

Cities Without Professional Drivers

Fears of widespread job loss as driving is automated may affect cities less than expected.

Long-haul trucking is a sector where angst over the downsides of automated driving is high. Some fear that full automation could put as many as 1.7 million drivers out of work. These job losses are likely to be concentrated outside cities, however.

But as the same technologies proved in long-haul trucking are applied to commercial fleets operating in urban areas, millions of jobs driving buses, delivery vehicles, and school buses will be at risk. **(FIG. 35)** The impact of AVs on taxi drivers could be particularly acute, as their numbers have swelled in recent years. A recent study at Oxford University found that Uber had enabled a 50 percent increase in the number of self-employed taxi drivers in the UK. These jobs are likely to be among the first to disappear.

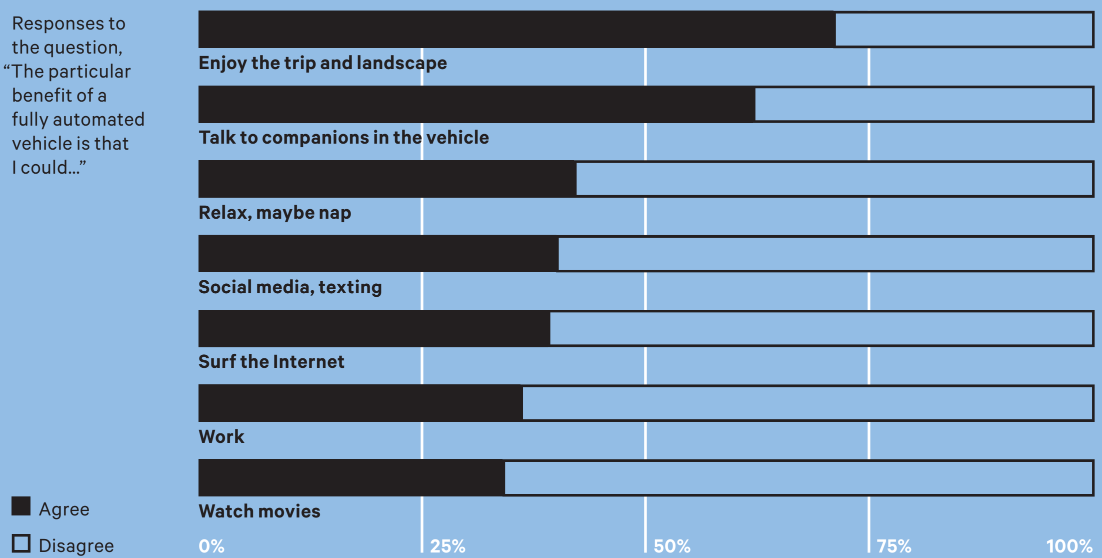
Engine of Growth

Could AVs also create jobs?

The question of direct employment related to the rollout of AVs has been almost entirely neglected. However, Toronto's 2015 study identified three sectors that could experience potential employment gains of up to 15 percent—construction related to conversion of parking facilities, expansion of highways and roads, and IT products and services directly related to AV rollout.

Indirect positive impacts on employment and overall economic health seem likely, however, as businesses will see the same dramatic drops in transport costs as consumers. AVs will enable the creation of new consumer products and services, contributing to economic growth. And AVs are likely to allow businesses to restructure and reorganize, increasing productivity.

FIG. 34 People Are Not Likely to Work in AVs



Source: Institute of Transport Research in Berlin

FIG. 35 Commercial Driving Jobs at Risk from Automation in the United States (2015)

Occupation	Avg Annual Wage	Total Jobs
Light truck or delivery services drivers	$33,870	797,010
Bus drivers (school or special client)	$29,910	499,440
Delivery drivers	$27,720	405,810
Postal service mail carriers	$51,790	307,490
Taxi drivers & chauffeurs	$25,690	178,260
Bus drivers (transit & intercity)	$39,410	158,050
		2,346,060

Source: Bureau of Labor Statistics

Human Services

Industrial cities treated social ills by building hospitals, schools, and community centers. The low-cost mobility of AVs could be just as important a tool for reorganizing and reinventing services in the future.

Most city governments devote the bulk of their spending to human services. Here we look at two of the most important contributors to well-being and how AVs might enable savings and innovation.

Children and Schools

Transportation takes a heavy toll on school spending. In the United States, some 25 million students (nearly 55% of those enrolled) are transported by bus an average cost of more than $960 annually per student. It's highly uncertain how parents will react to the idea of computers carrying their children to school—the safety record of early AVs will determine the actual risks involved and how they are perceived by parents. But AV buses could substantially reduce these considerable costs for local schools.

Beyond simply cutting costs, AVs could support restructuring of how education is delivered. Policy reforms that seek to increase choice and specialization in local school systems will increase school-related travel. The scant research that exists clearly shows that such magnet schools draw from a larger geographic area than neighborhood schools. As a result, magnet schools have lower rates of walking, bicycling, and commuting by car and higher rates of busing.

How can cities measure the impact of AV-enabled mobility on access to human services?

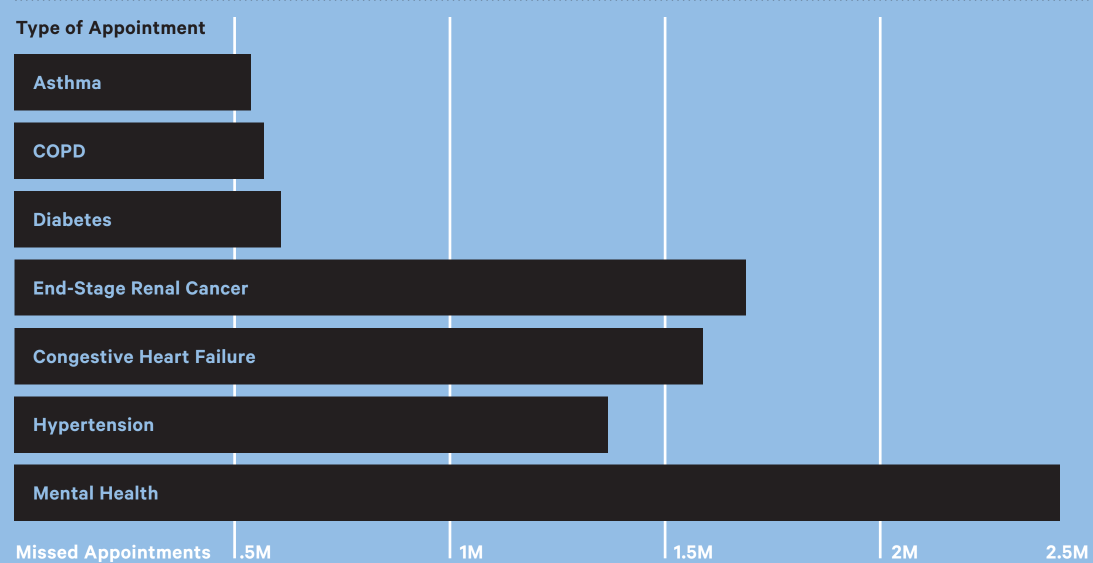
Health Care

While health care and medical services are restructuring according to many variables in different countries, we expect that overall standards of care and consumption of services will continue to increase. In many cities this will result in more frequent patient travel, to a larger number of treatment facilities, often over longer distances.

But transport options have not kept up with these shifts, especially for the disabled. According to a recent report published by the Ruderman Family Foundation and Securing America's Future Energy (SAFE), an estimated 11 million medical appointments are missed annually in the United States due to insufficient transportation. If AVs could fill this gap, an estimated $19 billion could be saved annually, most of it from public entitlement programs. **(FIG. 36)**

As AVs become the primary way people access health care, this will create new opportunities for rethinking how services are delivered. Unattended medical shuttles are unlikely, as many passengers will still require assistance boarding and de-boarding the vehicle. But the driver might be replaced by a more skilled medical technician who could perform triage and preventive care. As AI-enabled diagnostics, telemedicine, and other innovations improve, many patients could be treated on-board and discharged back at their homes. If significant amounts of care could be decentralized in this way, hospitals could be smaller or more specialized.

FIG. 36 AVs Could Eliminate Millions of Missed Medical Appointments (US)



Source: Ruderman Family Foundation

Public Finance

The transition to AVs threatens city revenue streams, such as parking. But it will also allow the creation of targeted taxes and fees that more effectively advance policy goals.

The elimination of driving won't mean big cutbacks in the city government workforce. Most cities employ a relatively small number of people whose sole function is driving. But AVs will still have widespread financial impacts.

Pricing Roads

The biggest financial opportunity AVs present cities is in restructuring how road systems are financed. In most countries, motorists pay high taxes on fuel but almost nothing for actual use of roads. This scheme is breaking down all over the world as roads become more congested and electrification looms.

To more fairly price access to urban streets, the use of congestion tolls has spread to many cities in recent years. AVs provide a critical opportunity where barriers to introducing these fees more widely may be significantly reduced. Research shows that motorists are much less sensitive to electronic toll payment than cash. Electrification will demand another innovation, distance-based road charges, to replace fuel tax revenues. Recently, analysts at McKinsey modeled the impacts of various AV deployment scenarios in London, New York, Los Angeles, and Delhi, forecasting 20 to 65 percent drops in energy tax revenues by 2030. **(FIG. 37)**

Properly used, these revenues could directly subsidize transit and shared AV systems (which might be exempted). This could reduce the burden on other sources of funding like property taxes and long-term debt. But since fuel taxes are mostly collected by higher levels of government, cities may find themselves hard-pressed to hold on to these new funds.

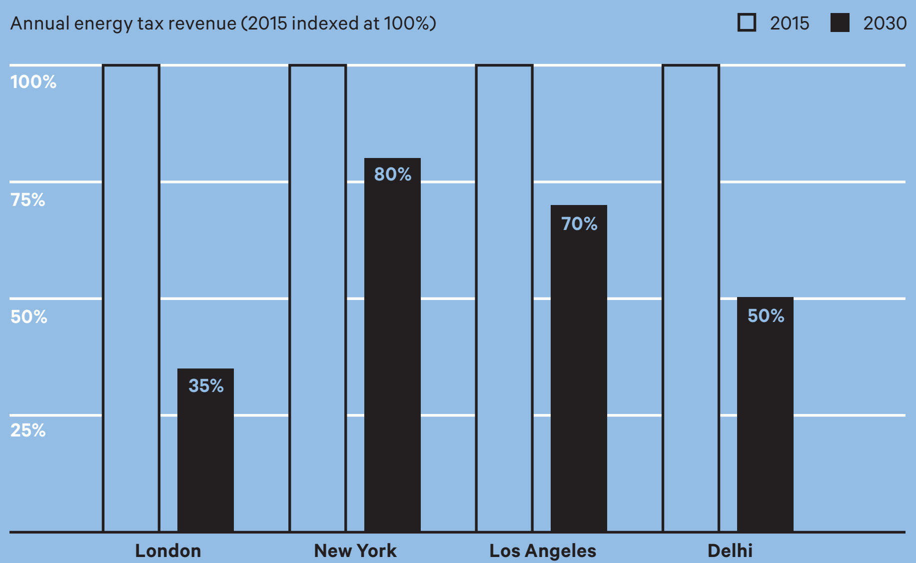
Shifting Fortunes for Transit

AVs could provide new ways to manage the fast-growing costs of demand-responsive services (or paratransit), which serve those unable to use conventional buses and trains. These systems are costly to operate, while fares are fixed, resulting in large operating deficits. **(FIG. 38)** Some cities are partnering with ride-source providers to serve these riders—only about 25 percent of which require specially equipped vehicles to handle wheelchairs. There is considerable resistance among disabled advocates. It's unclear how AVs would mitigate these factors, and they could actually increase costs—as drivers are eliminated, personnel would still be required to assist with boarding and medical emergencies.

Long-term Issues

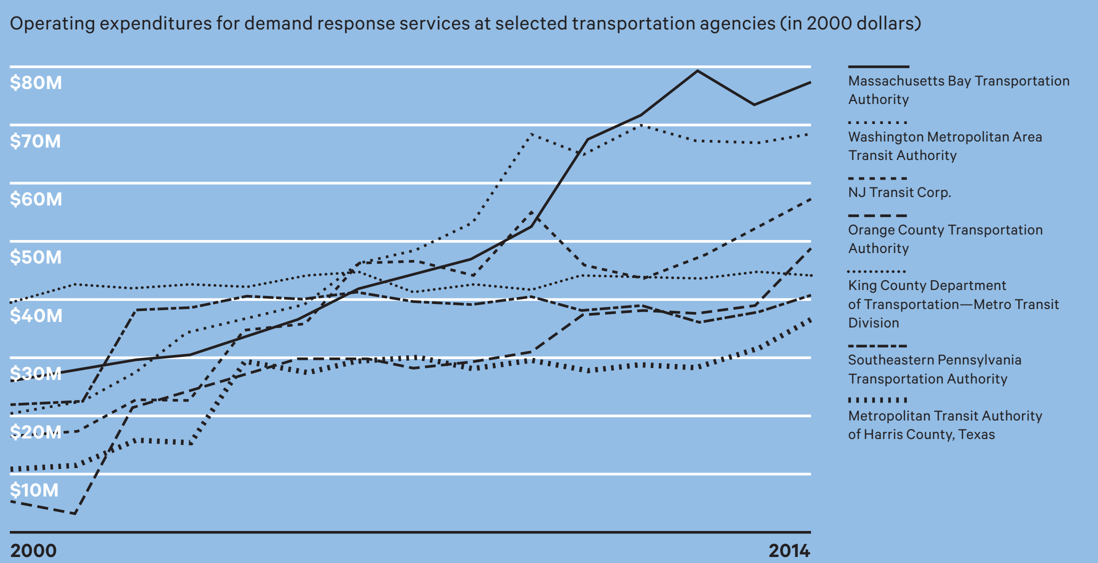
The long-term fiscal impacts of widespread use of AVs are highly uncertain. Property tax revenues could expand if AVs, especially shared taxis, unlock large amounts of land that can be rebuilt at higher densities. Self-driving sprawl on the other hand, could exacerbate capital flight and further erode the tax base of less desirable districts. Finally, long-term financing tools like revenue bonds would need to be restructured as traffic volumes shift. But AV-road pricing could help expand and drive innovation in these approaches.

FIG. 37 Potential Impact of Vehicle Electrification on Energy Tax Revenues



Source: McKinsey

FIG. 38 Paratransit is Eating Transit System Budgets



Source: The Brookings Institution

Land Use

The AV transition could unleash a reshuffling of homes and businesses that transforms the urban landscape.

Land and transportation costs are the yin and yang of urban development. Historically, transportation innovations that lowered the cost of travel have triggered the expansion of cities. In other words, the future is more likely to look like the outskirts of Mexico City than its central business district. **(FIG. 39)**

Self-Driving Suburbs and Computer-Choreographed Cities

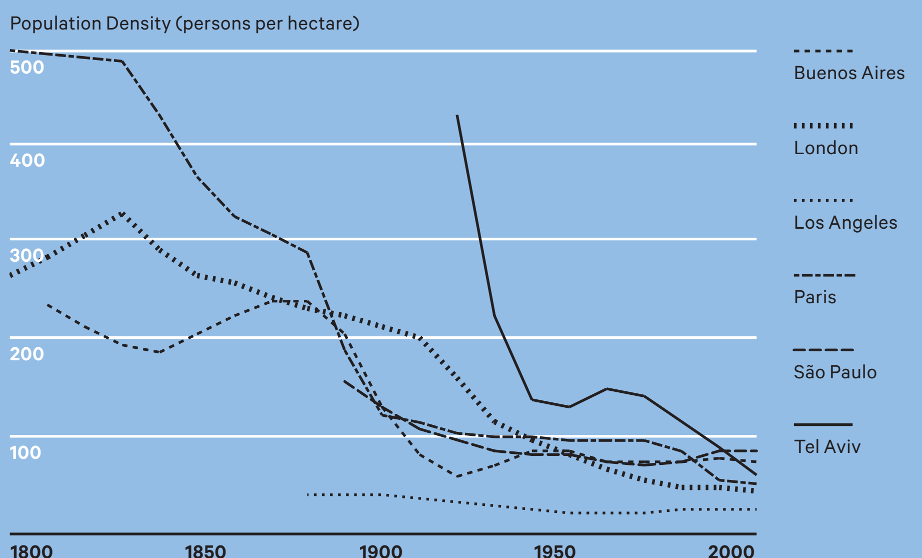
AVs have the potential to further fuel urban sprawl by reducing the inconvenience of long commutes. But they also offer intriguing new possibilities to increase the density and appeal of cities by making them more convenient, safe, and efficient.

One way to understand how AVs could push people closer together or pull them farther apart is to look at how they could impact current conditions in different parts of a city and its surrounding region. We imagine two alternative futures—one where shared AVs dominate, the other where private AVs do. **(FIG. 40)**

The End of Downtown Parking

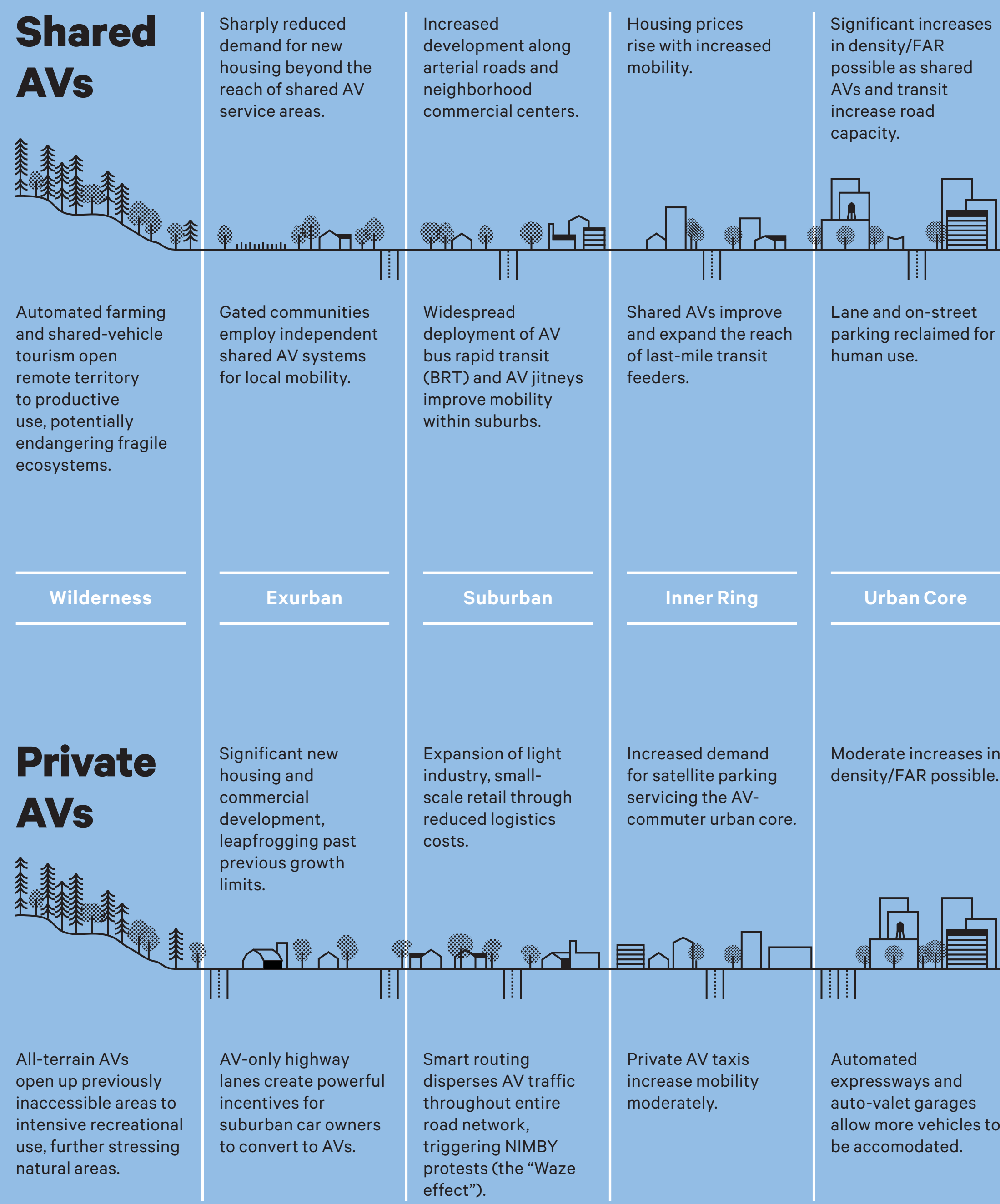
Nowhere are the land use impacts of AVs clearer than the dramatic reductions in parking requirements expected in city centers. In Los Angeles, an admittedly extreme case, off-street parking is the dominant land use. Much of this land will be repurposed as AV-enabled ride-sharing reduces the number of vehicles that need to be parked, or satellite self-park lots that cater to private AVs move to less costly outlying land. What few parking structures remain will be highly automated to increase capacity.

FIG. 39 Population Density Falls as Transportation Technology Enables Urban Expansion



Source: *Atlas of Urban Expansion*. Shlomo Angel, et al. 2012

FIG. 40 How AVs Might Change the Shape of Cities



Source: Bits and Atoms

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This horizon scan draws on a wide variety of publications by academic researchers, government agencies, industry analysts, and policy and planning think tanks. The diversity of topics, forecasts, and insights they contain reflects the inherent scope and uncertainty of the AV transition.

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Taming the Autonomous Vehicle:
A Primer for Cities

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Today, the pace of AV innovation is rapidly accelerating. But today's big leaps follow years of small steps forward.

The dream of a self-guided, self-propelled conveyance is one of humanity's oldest technological aspirations. Many of our most ancient myths feature magic carpets, levitating thrones, and flying chariots.

In the 20th century, the invention and mass production of automobiles was a major breakthrough on the road to achieving this age-old dream. And it set the stage for fully realizing the creation of machines that can not only move over land under their own power, but navigate on their own as well.

1000 BC Sailboats become the first automated vehicles, with self-steering mechanisms connecting a weather vane to the tiller.

1904 In Bilbao, inventor Leonardo Torres y Quevedo attaches an apparatus he calls a telekino to a tricycle, creating the first radio remote-controlled vehicle.

1914 Lawrence Sperry invents the autopilot in France, setting aviation on a rapid expansion path by reducing fatigue during long flights.

1920 US horse population peaks at about 25 million as motorization scales up.

1925 American Wonder, a remote-controlled driverless car developed by Francis Houdina is demonstrated on Broadway in New York City, drawing enormous crowds.

1935 AVs become prevalent in American pop culture.

GM's Chevrolet division releases a six-minute safety film, The Safest Place, urging drivers to abide traffic rules as effectively as a hypothetical "automatic driving mechanism."

A short story, "The Living Machine" published by David H. Keller in *Wonder Stories* imagines a driverless future. "Old people began to cross the continent in their own cars. Young people found the driverless car admirable for petting. The blind for the first time were safe. Parents found they could more safely send their children to school in the new car than in the old cars with a chauffeur.

1938 *Popular Science* publishes a widely read portrayal of self-driving cars steered by an electromagnetic guide-wide embedded in the road surface, transmitting pulses to regulate speed and steering.

1939 GM's historic Futurama exhibit at the New York World's Fair introduces the American public to an imagined world of 1960, where residents travel roads in cars equipped with electronic speed control and collision avoidance systems.

1939-1945 Wartime advances in automated fire control and radar lay the theoretical and technical foundations for digital sensing, computing, and communications systems that will enable modern AVs.

1958 The Chrysler Imperial becomes the first American car marketed with cruise control.

GM tests first 'automatically guided automobile' at GM Technical Center in the Detroit suburb of Warren.

1966–1972 Shakey, the first robot to navigate indoors autonomously rather than on preprogrammed routes is developed at SRI in Silicon Valley.

1967 British philosopher Philippa Foot first formulates a thought experiment dubbed the trolley dilemma. By posing hypothetical questions about how to evaluate the consequences of emergency decisions where harm to others cannot be avoided, her work became crucial to framing approaches to the ethics of robotics and autonomous systems

1975 The Morgantown Personal Rapid Transit system opens at West Virginia University, an early demonstration of a fully autonomous, on demand urban surface transportation system.

1977 The first truly autonomous car, which processes imagery from two onboard cameras to follow white street markers, is demonstrated at the Mechanical Engineering Laboratory in Tsukuba, Japan. It achieves a top speed of less than 20 mph.

1979 The Stanford Cart, a four-wheeled robot, successfully navigates a chair-filled room without human intervention using computer vision techniques. The trip takes five hours.

1987 Aerospace engineer Ernst Dickmanns of West Germany's Bundeswehr University Munich, hailed by many as the pioneer of the autonomous car demonstrates the VaMoRs prototype vehicle, travelling at speeds up to 56 mph (90 km/h).

1989 Researchers at Carnegie Mellon University begin work on ALVINN, the first AV prototype to use a neural network approach to process road imagery.

1991 The Intermodal Surface Transportation and Efficiency Act (ISTEA) is passed, committing the US government to an automated highway proof-of-feasibility demonstration.

1994 Two experimental AVs log over 625 miles in the final demonstration of the EU's PROMETHEUS project, travelling on three-lane highways around Paris, in heavy traffic, at speeds up to 80 mph (130 km/h) and marking the first time a machine vision system was used to control lane changing and passing.

1995 Members of Carnegie Mellon University's NavLab pilot a partially autonomous vehicle more than 2,000 miles from Pittsburgh to San Diego in a test dubbed "No Hands across America." Ernst Dickmanns's German team responds by taking its VaMP prototype on a blazing 110-mph, 1,000-mile trip along the autobahn from Munich to Denmark.

1997 A consortium led by the US Department of Transportation, GM, and Carnegie Mellon University demonstrates automated driving in multi-vehicle platoons along a 7.6-mile (12 km) stretch of I-15 north of San Diego. The system employed 93,000 guidance magnets embedded in the roadway.

2004 DARPA, the Pentagon's special research division, sponsors the Grand Challenge, gathering 15 teams in an AV design competition that requires navigating a rugged 142-mile wilderness course. No team successfully completes the course.

2005
The second DARPA Grand Challenge sees dramatic improvement over the same test course, with five of 23 finalists finishing.

2006
Masdar City, in Abu Dhabi, is the first newly planned town to be designed almost exclusively around AVs for internal transportation using a personal rapid transit system.

2007 The third DARPA Grand Challenge takes AVs into simulated urban terrain for the first time on a 60-mile test course. The unmanned vehicles obeyed California traffic laws while dealing with obstacles and performing tasks such as merging into traffic and navigating roundabouts.

2008 Komatsu delivers the first AV dump truck to the Gabriela Mistral copper mine in Chile.

2009 Google launches effort to develop an AV.

2010 Masdar's personal rapid transit system is scaled back to a demonstration line in the wake of the 2008 financial crisis.

2011 Nevada becomes the first American state to pass legislation specifically authorizing the operation of AVs.

2012 Voyager 1, an autonomous space probe launched in 1977, becomes the first man-made object to leave the solar system.

2013 Nissan marks Japan's entry into the AV race, demonstrating its Leaf AV prototype by, driving Prime Minister Shinzo Abe around a test loop nestled between the National Diet Building and the Imperial Palace.

2013 Volvo, in partnership with the city of Gothenburg, Lindholmen Science Park, and Swedish transport authorities, launches the first large-scale consumer test of AVs, involving 100 AVs on a 31-mile (50 km) network of commuter roads by 2017.

2014 MIT and National University of Singapore launch an AV pilot in the island nation's Jurong Lake district, using golf cart–sized electric vehicles.

2015 The United Kingdom launches its main AV testbed in the 1960s new town of Milton Keynes, led by the Transport Systems Catapult, a government-backed incubator.

The University of Michigan opens the Mcity AV testbed, a 32-acre simulated American community featuring streets, intersections, and traffic signs and signals.

2016 · January GM purchases Sidecar and takes a $500 million minority stake in Lyft, pledging a Chevy Bolt AV trial within a year.

2016 · March The UN Economic Commission for Europe updates the 1968 Vienna Convention on Road Traffic, a treaty that created considerable uncertainty about the legality of AVs due to a stipulation that "every driver shall at all times be able to control his vehicle." The new rules explicitly allow AV features as long as they can be overridden or switched off by the driver.

2016 · April Florida updates its original AV-enabling law to become the first state to permit remote monitoring of test vehicles on public roads with no backup operator in the vehicle.

The European Truck Platooning Challenge stages the first large-scale test of autonomous long-haul trucking, involving a dozen vehicles from Volvo, Daimler, and Scania converging on the Port of Rotterdam from locations across the continent.

2016 · May Google and Fiat Chrysler announce plans for joint development of 100 AV Chrysler Pacifica minivans, combining forces at a new Michigan R&D center.

2016 · June
The US Conference of Mayors adopts a resolution, sponsored by Beverly Hills, CA. Mayor John Mirisch, to encourage use of AVs for public transportation.

GM establishes a new AV test track at its Warren Tech Center, 58 years after the first guide-wire experiments in 1958.

The first urban AV minibus service launches in Sion, Switzerland, and is led by PostBus. Two shuttles operate on a fixed route in the city center. Services were suspended for two weeks in September, after one of the shuttles ran into the open tailgate of a parked delivery truck without injury, but have since resumed. The buses, which can carry up to 12 passengers and operate at speeds up to 15 mph, are made by French startup Navya.

2016 · August The first commercial AV taxi service launches in Singapore with six cars operating in the 2.5 square mile one-north tech district. The taxis still have a human backup driver and are summoned through an app where users can be picked up or dropped off in predetermined locations.

2016 · September Uber launches its first self-driving taxi fleet in Pittsburgh, PA, consisting of 14 Ford Fusion SUVs.

Two more urban AV minibus services launch in Lyon, France and Helsinki, Finland. Both systems use buses made by French startup Navya.

Washington, D.C. passes a law to permit small-scale pilot tests of deliverybots.

2016 · October An AV tractor-trailer developed by startup Otto makes the first autonomously driven commercial freight delivery, carrying 50,000 beers from Fort Collins to Colorado Springs.

2016 · November
Estonian startup Starship Technologies receives approval from Redwood City, CA, and Washington, D.C., for pilot testing of autonomous delivery bots.

Timeline continues with forecasts on page 26.