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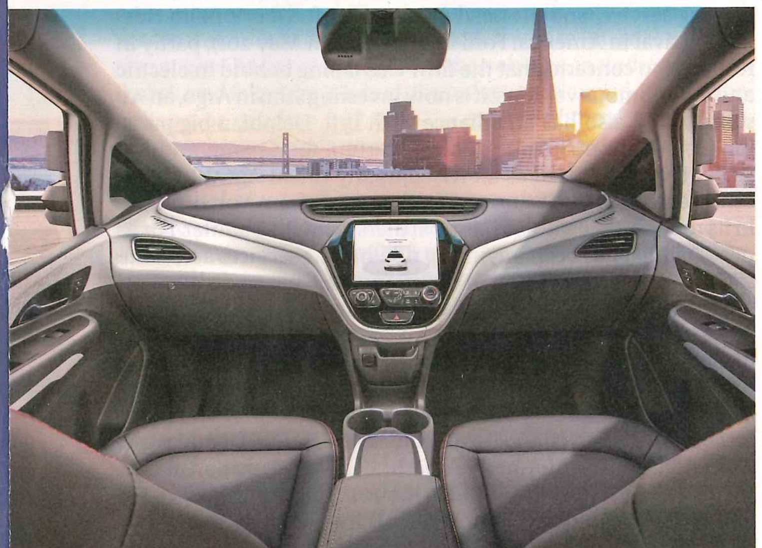
SPECIAL REPORT
AUTONOMOUS VEHICLES
March 3rd 2018

Reinventing wheels

Reinventing wheels

Driverless vehicles will change the world, just as cars did before them. What went wrong last time round holds valuable lessons for getting it right this time, says Tom Standage

EVERY DAY AROUND 10m people take an Uber. The company has made ride-hailing commonplace in more than 600 cities in 82 countries. But the Volvo XC90 picking its way through traffic on a wintry morning in Pittsburgh is no ordinary Uber. Climb into the back, and you will see a screen mounted between the front seats, showing a digital representation of the world around the car, with other vehicles, pedestrians and cyclists highlighted as clusters of blue dots. Tap the screen to say you are ready to leave, and the car starts to move. But no one is driving it. This Uber is an autonomous vehicle (AV)—a car that can drive itself.



Admittedly, Uber's self-driving robotaxi has a human sitting in the driving seat, but only to take over if something unexpected happens. The car drives carefully but confidently in downtown traffic and light snow, handling four-way stops, traffic lights and pedestrian crossings with aplomb. It even knows how to deal with drivers performing the "Pittsburgh left", a local custom that allows the first vehicle at a traffic light to turn left in front of oncoming traffic. The most noticeable difference from a human driver is that the vehicle makes no attempt to avoid Pittsburgh's notorious potholes, so the ride is slightly bumpy at times. The engineer in your correspondent's robotaxi takes over occasionally, for example to guide the car through roadworks where the lane markings have recently been changed.

Autonomous vehicles are not yet quite ready to operate without human supervision, then. But they have made rapid progress in recent years, and can now be seen on the roads in several American cities, easily identified by the clusters of sensors on their roofs. Uber's robotaxis ferry riders around in Pittsburgh and Phoenix. Waymo, Google's self-driving car unit which is now a separate company in the Alphabet family, has gone a step further, operating autonomous minivans in Chandler, a suburb of Phoenix, without safety engineers in the driving seat. It plans to launch a commercial ride-hailing service there this year. GM, America's biggest carmaker, hopes to launch a robotaxi service in 2019 using autonomous Chevy Bolt cars that do not even have steering wheels or pedals.

AVs operated by tech giants, startups and established carmakers can also be seen around Silicon Valley and Pittsburgh, America's two main hubs of the emerging industry, drawing on talent from Stanford and Carnegie Mellon universities respectively. In other parts of the world, driverless shuttles ferry passengers on university campuses, in business parks or along special bus lanes. AVs stole the show at CES, the world's biggest technology fair, in Las Vegas in January. Suddenly, it seems, everybody is jumping on the driverless bandwagon.

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ACKNOWLEDGMENTS

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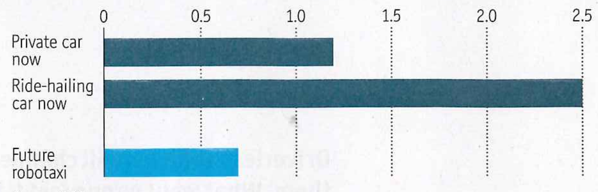
Recent progress in computer vision and other machine-learning systems is one reason. Tech folk from chipmakers to software firms see AVs as a lucrative new market for their products. Within the automotive industry, the rise of Uber and other ride-hailing services caused a “massive shift in perception around 2015”, says Sebastian Thrun, a pioneer of AVs at Stanford who led the development of Google’s first self-driving car. Carmakers realised that they needed to take AVs seriously—because they will redefine their industry.

The combination of autonomy and ride-hailing, together with a switch to electric vehicles, seems likely to undermine the logic of car ownership for many people. Ride-hailing services in the rich world currently cost around $2.50 per mile, compared with about $1.20 per mile to own and operate a private car (see chart). But the driver accounts for about 60% of the cost of ride-hailing. UBS, an investment bank, reckons that automation, competition and electrification (which makes cars more expensive to buy but much cheaper to run) will cut the cost of ride-hailing by 70%, to about $0.70 per mile. So a typical Western household driving 10,000 miles a year could ditch its car, use robotaxis and save $5,000 a year. And there are other advantages, explains Mr Thrun: “You can be drunk, you don’t have to look for parking, and your kids can take the car.”

“Once the car becomes autonomous, the relevance of car ownership drops materially,” says David Lesne of UBS. His firm predicts that robotaxis will take off rapidly after 2025, with 80% of people using them in cities, where available, by 2035. BCG, a consultancy, reckons that by 2030 a quarter of passenger-miles travelled on America’s roads will be in shared, self-driving electric vehicles, reducing the number of cars on city streets by 60%, emissions by 80% and road accidents by 90%. Though some people will want to own autonomous cars, about half of AVs will be shared robotaxis, says Nikolaus Lang of BCG. Globally, the “passenger economy” created by the convergence of autonomous vehicles and ride-hailing will be worth $7trn a year by 2050, says Strategy Analytics, a consultancy.

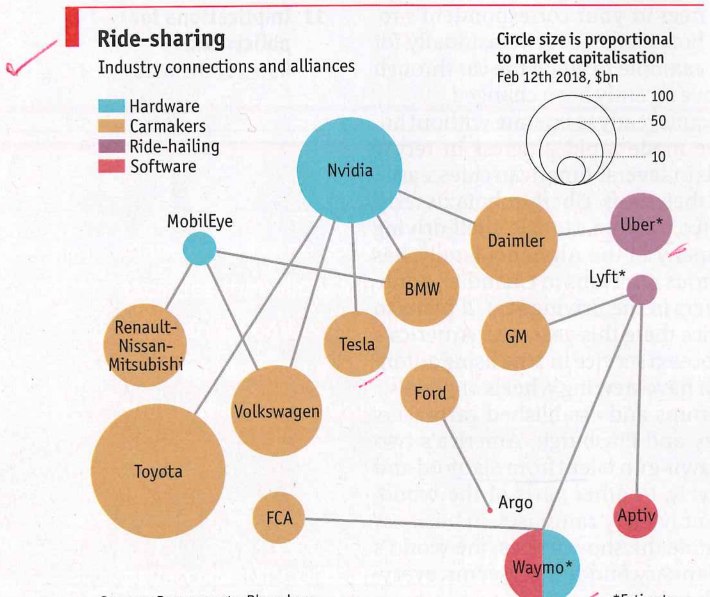
Carmakers, technology giants, startups and ride-hailing firms are already engaged in a furious battle to dominate this emerging industry. The carmakers understand metal-bashing, but know less about complex software. The tech firms know about machine learning and computer vision, but not making cars. The ride-hailing firms, for their part, have their apps installed on millions of users’ phones, providing the obvious route to market. The result has been a flurry of deals, much hedging of bets and a constantly evolving web of alliances (see chart).

Designated driver
Cost per mile, worldwide, $



Source: UBS

Ride-sharing
Industry connections and alliances



Sources: Press reports; Bloomberg

Mix and match

Intel, a chipmaking giant, bought Mobileye, a maker of autonomous-driving systems, for $15.3bn in March 2017. GM bought Cruise, an AV startup, for $1bn in March 2016, set up Maven, a car-sharing service, and invested $500m in Lyft, Uber’s main ride-hailing rival in America. Ford fired its CEO in May 2017, partly in response to concerns that the firm was falling behind in electric and autonomous vehicles; it is now investing $1bn in Argo, an AV startup, and also has an alliance with Lyft. Delphi, a big parts-maker, bought nuTonomy, an AV startup, for $450m, and has since reinvented itself as an AV company called Aptiv. Uber recently agreed to buy 24,000 self-driving cars from Volvo, for use in its robotaxi fleet; it also has a partnership with Daimler. For its part, Daimler has been buying up ride-hailing services across Europe and the Middle East that compete with Uber, and also owns a car-sharing service. Volkswagen, Europe’s biggest carmaker, has struck a deal with Aurora, an AV startup founded by veterans of Google, Uber and Tesla. And so on.

In short, the tectonic plates of technology and carmaking are colliding, heralding a carquake. This seismic shift will transform both industries, and its aftershocks will be felt far and wide: AVs will be as transformative a technology as the smartphone. Just as cars reshaped the world in the 20th century, in ways good and bad, AVs could change how people live, work and play. They could dramatically reduce the number of road deaths, the time spent sitting in traffic and the space wasted on parking. In urban planning, AVs provide “a great opportunity to address a lot of problems at the same time”, says Joel Kotkin, an urban-studies expert at Chapman University in Orange, California. “If the 20th century was about cars giving us independence, the 21st will be about autonomous vehicles giving us independence from cars,” says Justin Erlich, head of policy for AVs at Uber.

But just as cars had unexpected side-effects, AVs are raising new concerns about safety, cyber-security, liability and inequality. “Autonomous vehicles will open a Pandora’s box of unintended effects,” says Peter Norton, a social historian at the University of Virginia. A century ago cars promised to provide safe, fast and congestion-free transport. The similarities with the claims now being made about AVs are “eerie”, notes Mr Norton. This special report will assume that the technological hurdles to full autonomy can be overcome. It will consider the implications of AVs for personal mobility, car ownership and carmaking, but will also look at the wider economic, social and cultural knock-on effects. How will everyday activities be transformed? How could AVs reshape cities? And what lessons does the rise of the car in the 20th century hold for driverless vehicles in the 21st? ■

Technology

From here to autonomy

Making vehicles drive themselves is hard, but getting easier

THE MODERN AUTOMOTIVE era began with a competition. In the early 1890s there was much interest in the emerging technology of horseless carriages, which promised to combine the speed of a train with the flexibility of a horse and the convenience of a bicycle. *Le Petit Journal*, a French newspaper with a knack for publicity stunts, decided to hold a contest to discover the best method of propulsion: steam, electricity or petrol engine. It invited entrants to drive from Paris to Rouen, a distance of 79 miles. Their vehicles would be judged not by their speed but whether they were safe, easy to use and economical to run.

The competition, held in July 1894, attracted crowds of onlookers as 21 contraptions set out from Paris. Only 17 vehicles stayed the course; along the way, seven dogs were run over and one cyclist was injured. The clear winner was not a direct participant but an inventor: Gottlieb Daimler, whose internal-combustion engine had powered nine of the vehicles, including the four that shared first prize. He had, the judges proclaimed, “turned petroleum or gasoline fuel into a practical solution” for self-propelled vehicles, which were starting to be referred to in French as “automobiles”. Daimler’s victory helped establish the supremacy of petrol-powered cars in the 20th century, and the term automobile soon spread into English and other languages.

Fittingly, the modern era of autonomous vehicles also began with a competition, held in March 2004 in the Mojave desert. It was organised by DARPA, America’s main military-research agency, and required driverless vehicles to navigate a 150-mile off-road course. A total of 21 teams qualified, but after pre-contest trials and mishaps only 12 vehicles crossed the starting line. Amid mechanical failures and encounters with ditches, none of them made it to the finish. Carnegie Mellon’s Sandstorm, the vehicle that did best, travelled 7.4 miles before getting stuck; as it tried to free itself, its front wheels caught fire.

Learner non-driver

It seemed that DARPA had set the bar too high. Yet when it held another competition in October 2005, five of the 23 participants completed the entire 132-mile course, and all but one beat the 7.4-mile record from the previous year. The winning vehicle was built by a team from Stanford University led by Sebastian Thrun; Sandstorm finished second. In just 18 months, autonomous driving had gone from hopeless to feasible. In a third DARPA contest, in November 2007, vehicles had to complete tasks in a simulated urban environment, coping with road signs, traffic signals and other vehicles. Six out of 11 teams completed this much more complex challenge.

Encouraged by this rapid progress, Google set up a self-driving car project in 2009, led by Mr Thrun. Since then the participants in the various DARPA contests have gone on to work on autonomous-vehicle technology at Google, Uber, Tesla and a host of startups. Prototype self-driving cars first took to America’s public roads in 2012; they have since travelled millions of miles and have become steadily more capable. But the technology is not ready for mass deployment just yet. A fully autonomous car must solve three separate tasks: perception (figuring out what is going on in the world), prediction (determining what will happen next) and driving policy (taking the appropriate action). The last of these is the simplest, making up just 10% of the problem, says Mr Thrun; perception and prediction are the hard parts.

I see

Autonomous cars perceive the world through a combination of sensors including cameras, radar and LIDAR—a radar-like technique that uses invisible pulses of light to create a high-resolution 3D map of the surrounding area. The three complement each other. Cameras are cheap and can see road markings, but cannot measure distance; radar can measure distance and velocity, but cannot see in fine detail; LIDAR provides fine detail but is expensive and gets confused by snow. Most people working on autonomous vehicles believe a combination of sensors is needed to ensure safety and reliability. (Tesla is a notable exception: it hopes to achieve full autonomy without the use of LIDAR.) High-end LIDAR systems currently cost tens of thousands of dollars, but startups are devising new solid-state designs that should eventually reduce the price to a few hundred dollars.

Having combined the data from its sensors, the car needs to identify the items around it: other vehicles, pedestrians, cyclists, road markings, road signs and so forth. Humans are much better at this than machines, which have to be trained with lots of carefully labelled examples. One way to obtain them is to pay people to label images manually. Mighty AI, based in Seattle, has an online community of 300,000 people who carefully label images of street scenes for a range of automotive clients. “We want cars to have human judgment,” says Mighty AI’s boss, Daryn Nakhuda, “and for that we need human expertise.” Imagery from video games such as “Grand Theft Auto”, which features strikingly realistic street scenes, can also help. Because the game software knows what everything is, it can label such scenes with perfect accuracy, allowing them to be used for training.

The hardest things to identify, says Mr Thrun, are rarely seen items such as debris on the road or plastic bags blowing across a highway. In the early days of Google's AV project, he recalls, "our perception module could not distinguish a plastic bag from a flying child." Puddles on the road also caused confusion. Combining data from multiple sensors, however, can reveal whether an item in the road is a solid obstacle or not. Cars can also compare their sensor readings with those gathered previously by other cars on the same road, learning from each other's experiences in a process called "fleet learning". That gives an edge to firms with thousands or millions of miles of self-driving experience under their belts; but some startups also create and sell ready-made high-resolution maps for use by AVs.

Once a vehicle has identified everything around it, it needs to predict what will happen in the next few seconds and decide how to respond. Road signs, traffic lights, brake lights and turning signals provide some clues. But AVs are at a disadvantage to human drivers, who are used to dealing with exceptions to the normal flow of traffic, such as roadworks, broken-down vehicles, delivery trucks, emergency vehicles, fallen trees or bad weather. Snow is a particular challenge: LIDAR systems must be carefully tuned to ignore falling snow, and accumulations of snow on the roads make high-resolution street maps less accurate.

While the technology is still being developed, it helps to stick to limited areas that have been mapped in detail and generally have good weather. That explains why Phoenix, with its sunshine and regular grid system, is a popular place to test AVs. Pittsburgh is considered more difficult because of its harsher weather. Cruise, an AV startup now owned by GM, has demonstrated some impressive autonomous driving in the complex streets of downtown San Francisco. Kyle Vogt, Cruise's boss, argues that testing in densely populated environments means cars experience unusual situations more often, and thus learn faster.

When an AV gets confused and does not know how to respond, or makes the wrong decision, the safety engineer in the driving seat takes over. This is known as a "disengagement", and the number of disengagements per 1,000 miles travelled provides a crude measure of how the companies developing AVs compare (see chart). Disengagements are best seen not as failures but as learning experiences that help AV systems improve. Sensor data recorded in the lead-up to a disengagement can reveal what the car got wrong, says Noah Zych, head of safety at Uber's AV unit. Modifications to its software can then be tested in simulation. "We can play it back again and again, vary the scenario and see the distribution of outcomes," says Mr Zych. The improved software is then rolled out in real cars.

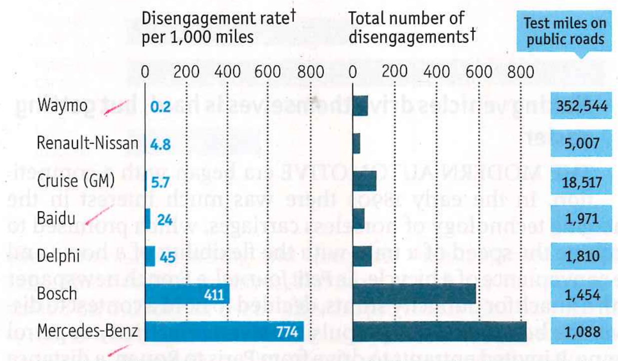
The public seems concerned mainly about two potential risks associated with AVs: ethical dilemmas and cyber-attacks

What do I do now?

Even when AVs are widely deployed, they will probably still need to ask for human assistance sometimes. Consider an AV caught behind a broken-down truck on a two-lane road with a solid line down the middle, says Christophe Sapet of Navya, a maker of driverless shuttles. Because it has been programmed to obey road markings, the AV will get stuck. Human drivers would simply bend the rules and drive around the truck when the road is clear. Navya's AVs instead call a remote supervision centre, where a human operator can see live feeds from their cameras. Rather than controlling such a vehicle remotely, the operator gives it temporary permission to cross the white line when it is

I give up

Testing of autonomous vehicles in California*
December 2016-November 2017



Source: California Dept. of Motor Vehicles
*Ford, Tesla and Uber do not test in California
†Self-driving mode stopped owing to system error or human intervention

safe to do so. Mr Thrun suggests such operators could, in future, end up supervising thousands of AVs at a time.

Meanwhile, limited forms of autonomy are being gradually added to existing production cars. A scale devised by the Society of Automotive Engineers defines the levels of autonomy. Level 1 involves basic assistance (such as cruise control). Level 2 adds features such as lane-keeping, allowing the car to drive itself on highways, but still requiring the driver to pay full attention. The new Audi A8, launched this year, is the first car to achieve level 3, which means it can drive itself and monitor its surroundings, but the driver must take back control when asked.

Waymo, Uber and others are attempting to jump directly to level 4, which provides full autonomy under certain conditions, such as in a specific part of a city. Some in the industry consider the partial automation of levels 2 and 3 to be unsafe, because drivers are still required to pay attention even when they have handed over control of the vehicle, which they find hard to do. (The driver of a level 2 Tesla Model S was killed when his vehicle hit a lorry in May 2016; investigators found that despite warnings from the car, he failed to keep an eye on the road.)

One problem for AVs is that the world was built to cater for human drivers, with whom they must share the roads. Humans communicate by flashing their lights and using other non-verbal cues, which (like other driving customs) can vary from place to place. AVs will probably end up being tuned to fit in with their surroundings, driving more aggressively in Boston than in California, for example, suggests Amnon Shashua, the boss of Mobileye, a maker of autonomous-driving technology.

"You have to make the vehicle so it can operate in the world as it is today," says Chris Urmson of Aurora, an autonomous-driving startup. But things should get easier in future. There may be road lanes or entire districts dedicated to AVs, and special equipment to support them, known as vehicle-to-infrastructure (V2I) technology. Already, in some areas where AVs operate, traffic lights have been modified to tell approaching vehicles when they will change. In future, V2I and V2V (vehicle-to-vehicle) technology should allow AVs to co-ordinate their actions better.

The public seems concerned mainly about two potential risks associated with AVs. The first is how they should respond to ethical dilemmas: say, choosing between hitting a group of children in the road or swerving and hitting another vehicle. Many people working in the field think that such questions do not reflect the real world, and point out that the best course of action is usually to slam on the brakes. AVs have superhuman, 360-degree perception and much faster reaction times, notes Danny Shapiro of NVIDIA, a chipmaker whose products power AVs.

The second worry is about cyber-attacks. AVs, which are essentially computers on wheels, could be remotely hijacked or sabotaged. Engineers working on AVs insist that they take cyber-security very seriously, and say that the multiple redundant sensor and control systems they build in to make a vehicle mechanically safe will also provide some protection. If any part of the vehicle starts to behave strangely, for whatever reason, it will stop. "It is easier to use an ordinary vehicle to kill people than to take control of a driverless car," says Mr Sapet.

AVs are on the cusp of working on public roads, at least in orderly environments with good weather. "Once you can crack that nut, it's incremental," says Mr Urmson. For his part, Mr Thrun has moved on to a new challenge: building cars that fly. Automotive bosses think he is crazy, he admits. But until quite recently they were just as sceptical about self-driving cars. ■

The impact on industry

Selling rides, not cars

Carmakers, tech companies and ride-hailing firms are all fighting for a piece of the action

IF YOU WANT to buy a fully self-driving car, you may have to wait for another decade. Autonomous vehicles will initially be offered for sale not to private owners but to robotaxi-fleet operators, for two reasons. First, LIDAR sensors are still so expensive that, deployed in production cars, they would cost more than the rest of the vehicle put together. For AVs in a robotaxi fleet, that is less of a problem, because vehicles will be operating, and thus generating revenue, throughout the day, whereas private cars are in use only about 5% of the time.

Second, getting AVs to work safely and reliably is much easier if their geographical range is limited to places that have been mapped in fine detail, such as city centres. So your first ride in an AV will be in a vehicle you hail using an app, not one you own.

Quality time

Waymo, Alphabet's AV effort, is testing a robotaxi service in Chandler, a suburb of Phoenix, and hopes to launch a commercial service later this year. Uber is operating driverless taxis in parts of Phoenix and Pittsburgh; users who hail a ride may find themselves being picked up by an autonomous car, supervised by an engineer (Uber gives riders the option to use an ordinary car instead if they prefer). Voyage, an AV startup, runs a robotaxi service in The Villages, a retirement community in San Jose, and is expanding to a second location, in Florida. Navya, a French startup, is operating an eight-seater autonomous shuttle bus in downtown Las Vegas, with three stops along a 1km (0.6 mile) route. It also has shuttles running in several other cities around the world, as does Easymile, a rival French firm. Large-scale deployments of AVs are most likely to start with geofenced robotaxi services in parts of cities such as Singapore or Dubai, and then expand over several years, predicts Nikolaus Lang of BCG.

It is likely to be many years before AVs are cheap enough for individuals to buy them, and capable enough to operate outside predefined, geofenced areas. Meanwhile, the roll-out of cheap robotaxis in urban areas might encourage many young urbanites, who are already going off car ownership anyway, to abandon it altogether. The combination of ride-hailing and autonomous-driving technology confronts carmakers with "the most profound challenge to their business models in a century", declares a recent report from BCG. That is why carmakers are now piling into ride-hailing and car-sharing services and pushing on with their own AV programmes. In an autonomous future where ownership is optional, they need to be selling rides, not cars.

This shift offers carmakers a big opportunity. The car market is worth around $2trn a year globally, whereas the market for personal transport is worth as much as $10trn, according to Morgan Stanley, a bank. But it also exposes them to new competitors, in the form of technology companies and ride-hailing networks. Some carmakers have launched their own mobility services; others may prefer to act as fleet managers, providing capacity for ride-hailing operators and charging them by the mile. Some will even make "white label" fleets badged with the name of a city or a ride-hailing network, rather than their own brand.

Robotaxi fleets running around the clock will generate predictable yields that will appeal to institutional investors. Turning themselves into asset managers for such fleets would be a logical step for carmakers, whose finance arms are already involved in fleet management, says David Lesne of UBS.

Pricing models for users will change, too: Uber is already testing telecoms-like monthly price plans in some cities, which include a certain number of rides or miles for a fixed price, just as a mobile calling plan offers a certain amount of calls, texts and data.

One big question is the effect of AVs on the number of vehicles sold worldwide per year, currently around 80m. Since most cars sit unused 95% of the time, switching to shared robotaxis that operate around the clock could greatly reduce the number of vehicles on the road. UBS reckons the global fleet size will halve by 2030 (see chart, next page). But if robotaxis are in use 50% rather than 5% of the time, they will need to be replaced far more often, says Johann Jungwirth, chief digital officer of Volkswagen. So unless vehicle lifespans can be greatly extended, the number of new vehicles needed each year will rise.

Making vehicles reliably in large quantities is hard, as Tesla's production problems have shown. "The core expertise that we've had for decades is excellent manufacturing," says Ponz Pandikuthira, head of product planning for the European arm of Nissan. So even in a world of robotaxis, being a carmaker could still be a big business—just a different one from what it is today. After 130 years making hardware, says Mr Jungwirth, "we need to take software and services just as seriously." That requires taking on new staff, retraining, acquisitions and partnerships. AVs will also accelerate the switch to electric vehicles, which have fewer components and need fewer assembly workers.

Form follows function

It will not just be carmakers that change shape; so will cars. Just as early "horseless carriages" resembled horse-drawn carriages, without the horse, most autonomous vehicles today are ordinary cars, retrofitted to drive themselves. But take away the need for a steering wheel and pedals, and AVs can assume a much wider range of shapes and sizes; Volkswagen's Sedric and the Mercedes-Benz F015 are pods in which passengers sit facing each other. Future AVs may need to allow for some physical separation of passengers to encourage people to share vehicles with strangers, says Karl Iagnemma of nuTonomy, while families might hail a different vehicle that lets everyone sit together.

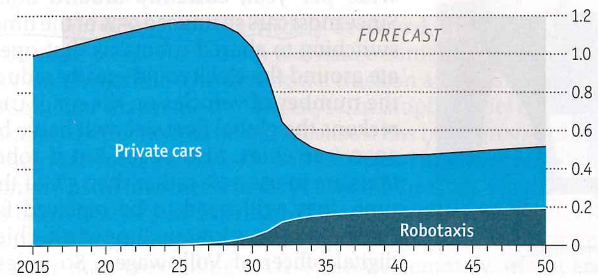
All this is bad news for car dealers. Most are barely profitable now and make their money from car financing and servicing, so even a small shift from car ownership to shared robotaxis could hit them hard. Repair shops and partsmakers could also suffer, assuming AVs reduce the number of car accidents. Already, some parts suppliers are listing AVs as a threat to their future profitability in regulatory filings. Insurers would be hit hard by a fall in private car ownership and fewer accidents. Healthcare providers and personal-injury lawyers would also suffer if there were fewer accidents, though few will feel sorry for them.

People who drive taxis, delivery vehicles and trucks are most directly threatened by AVs. Uber and Lyft say they will continue to need human drivers on some routes for years to come, but driving jobs might be redefined rather than abolished. Delivery drivers could be employed to manhandle large packages into customers' homes. Truck drivers might become overseers of platoons of vehicles travelling on highways. And AVs will create new jobs for remote fleet supervisors and mobile repair workers.

It already seems clear that AVs will cause the car industry and its adjacent businesses to change shape dramatically over the next couple of decades. But the consequences will not stop there. Like cars before them, AVs are sure to have far-reaching cultural and social effects too, most obviously in cities. ■

Decongestion charge

Number of urban vehicles worldwide, bn



Source: UBS

Urban planning

The new autopia

How autonomous vehicles will reshape cities

MODERN CITIES, PARTICULARLY in America, are habitats for cars as much as people, devoting huge amounts of space to roads and parking. "America is a great place to be—if you're a car," says Donald Shoup of the University of California at Los Angeles. The expectation that people should be able to drive anywhere, encountering little or no congestion on the way and parking at their destination, led to a splurge of construction in the 20th century. Urban freeways, commuter suburbs and mandatory parking requirements reshaped cities. Now AVs promise to transform them once again, undermining many car-centric assumptions made in the 20th century, opening up new possibilities and turning urban-planning debates upside down. "For the first time in a generation, we can really rethink what suburban development looks like," says Alan Berger, a professor of urban studies at the Massachusetts Institute of Technology.

Simply put, building cities around cars increases congestion, discourages the use of public transport and encourages sprawl, all of which urban planners generally disapprove of. The odd thing is that AVs could either reverse or accelerate each of these trends. They could reduce or increase traffic; make affordable transport more or less accessible; and lead to denser cities or more sprawl. It all depends on the rules for their use, and in particular the pricing. AVs know exactly where they are at all times, which makes it much easier to introduce fine-grained road tolls and congestion charges based on time of day, traffic levels and so on. That makes them a powerful and flexible policy tool.

Start with congestion. A switch to shared robotaxis could increase vehicle occupancy rates, reducing the number of vehicles needed to move people around and easing congestion. But low-cost robotaxis might also encourage more people to take more trips—the familiar problem of "induced demand" when road travel is cheap and easy. The roads could also fill up with autonomous delivery vehicles with nobody on board. The nightmare scenario, says William Riggs of the University of San Francisco, is that "we create another form of congestion—it just happens to be automated congestion." But careful pricing of roads and rides should be able to prevent that. Some cities already have congestion-charging schemes of various kinds, or rules to encourage vehicle-sharing, such as dedicated car-sharing lanes. Some are starting to price access to kerb space, for example at airports. AVs would allow far more subtle forms of charging, taking account of time, place, vehicle type, number of riders, traffic levels and so forth, to maximise sharing and minimise congestion. "It will be that interplay that ensures we don't end up with highly congested roads," says Justin Erlich of Uber.

What about the impact on public transport? A study by UC Davis found that among Uber and Lyft riders in America, bus use fell by 6% and light-rail use by 3%. AVs would be cheaper, so they could draw even more people away from public transport and onto the roads. This might discourage further investment in public transport, which in turn could create more "transit deserts" where large numbers of people (typically the poor and the elderly) depend on public transport but get an inadequate service. The economics of robotaxis will work best in dense urban centres, says Mr Riggs, so "we could see social-equity implications around the fringes of cities." But again, there is also a rosier scenario. Using AVs for the "last mile" to move people to and from railway stations could make public transport more viable in less densely populated areas. Some cities might also operate their own robotaxi fleets, or subsidise rides in poor neighbourhoods using toll revenues collected in rich ones.

Using AVs for the "last mile" to move people to and from railway stations could make public transport more viable in less densely populated areas

The emergence of AVs helpfully coincides with a change in the structure of cities, says Shlomo Angel, an urban-studies expert at New York University. He argues that the monocentric model, with a centre surrounded by suburbs, is a thing of the past. In many large American and European cities, jobs are moving from downtown to the periphery, and workers increasingly commute from one suburb to another, rather than to and from the centre. His analysis shows that 75% of jobs in a typical American city are outside the urban centre. In European and Asian cities with dense public-transport networks this decentralisation is easier to cope with, but retrofitting the necessary infrastructure onto American cities would be too expensive. "American cities need door-to-door transport systems to get to work, and driverless cars will play this role beautifully," says Mr Angel. Robotaxis hailed on demand promise to be a lot more efficient than privately owned vehicles, he says, and are well suited to the spatial structure of both present and future American cities. Mr Berger agrees. "It's not affordable to build mass transit that goes from suburb to suburb," he says. "The best solution I've seen in my career is the idea of shared autonomous vehicles."

That raises the question of urban sprawl. On the one hand, a switch to shared AVs by urban dwellers could lead to denser cities as some of the space currently used for parking is reallocated to housing. New high-density housing is already being planned with pick-up and drop-off zones for ride-hailing vehicles, and fewer parking spaces. On the other hand, AVs could also encourage sprawl by making long commutes more acceptable, because riders will be able to work or even sleep on the move. "The biggest negative of suburban living is the driving and the amount of space that has to be devoted to cars," says Joel Kotkin of Chapman University. By doing away with driving and making city centres easier to access, AVs will increase the appeal of suburban living. So it seems likely that AVs will make cities both denser and more spread out, depending on the road-pricing regime.

Turning back the clock

AVs could also make possible new kinds of suburbs, updating the 20th-century dream of garden cities. "Over the last 100 years our landscape has been drastically altered by the automobile," says Mr Berger. With AVs, "all the land we've given to the automobile can be put back into landscape and ecological functions." By doing away with parking and using one-way, single-lane roads that loop through neighbourhoods, the area of paved surface can be reduced by 50%, he calculates. That means more space for plants, more biodiversity and better water retention, reducing the risk of flooding in the urban core. Suburbs will have enough space to generate their own solar power or grow their own food.

City centres will end up looking different, too. In effect, cities have banked a large amount of valuable real estate in the form of parking lots and garages, notes Peter Norton of the University of Virginia, and must decide how to spend their windfall. Housing is one obvious use; parks are another. Some streets could be reconfigured to more imaginative uses than high-volume thoroughfares, he suggests. In particular, some quieter streets could become spaces where pedestrians and slow-moving AVs share the roadway as equals, with neither having priority. This would mark a return to the way streets worked a century ago, before cars took over. "Streets should not just be roads for cars but places for people," says Mr Shoup.

In retrospect, many drawbacks associated with cars in the 20th century arose from a failure to price their use properly. With appropriate pricing, AVs should be able to avoid many of those problems, giving urban planners and policymakers a much wider range of choices about how cities and transport systems could be structured. The challenge will be to choose wisely. ■

Society

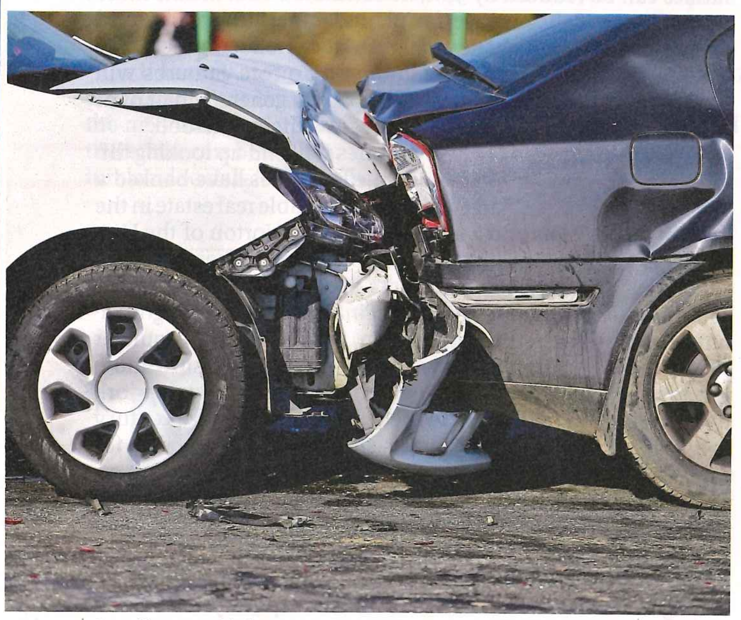
A different world

Foreseen and unforeseen consequences

ROAD TRIPS. DRIVE-THROUGHS. Shopping malls. Freeways. Car chases. Road rage. Cars changed the world in all sorts of unforeseen ways. They granted enormous personal freedom, but in return they imposed heavy costs. People working on autonomous vehicles generally see their main benefits as mitigating those costs, notably road accidents, pollution and congestion. GM's boss, Mary Barra, likes to talk of "zero crashes, zero emissions and zero congestion." AVs, their champions argue, can offer all the advantages of cars without the drawbacks.

In particular, AVs could greatly reduce deaths and injuries from road accidents. Globally, around 1.25m people die in such accidents each year, according to the WHO; it is the leading cause of death among those aged 15-29. Another 20m-50m people are injured. Most accidents occur in developing countries, where the arrival of autonomous vehicles is still some way off. But if the switch to AVs can be advanced even by a single year, "that's 1.25m people who don't die," says Chris Urmson of Aurora, an AV startup. In recent decades cars have become much safer thanks to features such as seat belts and airbags, but in America road deaths have risen since 2014, apparently because of distraction by smartphones. AVs would let riders text (or drink) to their heart's content without endangering anyone.

Evidence that AVs are safer is already building up. Waymo's vehicles have driven 4m miles on public roads; the only accidents they have been involved in while driving autonomously were caused by humans in other vehicles. AVs have superhuman perception and can slam on the brakes in less than a millisecond, compared with a second or so for human drivers. But "better than human" is a low bar. People seem prepared to tolerate deaths caused by human drivers, but AVs will have to be more or less infallible. A realistic goal is a thousandfold improvement over human drivers, says Amnon Shashua of Mobileye, a maker of AV technology. That would reduce the number of road deaths in America each year from 40,000 to 40, a level last seen in 1900. If this can be achieved, future generations may look back on the era of vehicles driven by humans as an aberration. Even with modern safety features, some 650,000 Americans have died on the roads since 2000, more than were slain in all the wars of the 20th century (about 630,000).



Goodbye to all that

To take advantage of much lower operating costs per mile, most AVs are almost certain to be electric, which will reduce harmful emissions of two kinds: particulates, which cause lung and heart diseases, and climate-changing greenhouse gases. Even electric vehicles, however, still cause some particulate emissions from tyre and road wear, and the drop in greenhouse-gas emissions depends on how green the power grid is. The switch to electric vehicles will require more generating capacity (UBS estimates that it will increase European electricity consumption by 20-30% by 2050) and new infrastructure, such as charging stations and grid upgrades. For urban dwellers, the benefits will be better air quality and less noise.

Whether AVs will be able to reduce congestion is much less clear. The lesson of the 20th century is that building more roads to ease congestion encourages more car journeys. If robotaxis are cheap and fast, people will want to use them more. Yet there are reasons to think that the roads would become less crowded. Widespread sharing of vehicles would make much more efficient use of road space; computer-controlled cars can be smart about route planning; and once they are widespread, AVs can travel closer together than existing cars, increasing road capacity.

What is certain is that riders who no longer have to drive will gain an enormous amount of time that can be used to work, play or socialise. "Americans can take back a total of 30bn hours per year that they now spend driving, sitting in traffic or looking for a parking space," says BCG.

Yet to think about AVs as a fix for the problems caused by cars is to risk falling into a familiar historical trap. This is exactly how people thought about cars when they first appeared: as a fix for the problems caused by horses. In the 1890s, big cities around the world were grappling with growing volumes of horse manure and urine and the rotting bodies of thousands of dead horses, spreading disease. In 1894 the *Times* of London famously predicted that by the 1940s every street in the city would be buried under nine feet of manure. By comparison, cars seemed clean and hygienic, a key reason why they were adopted so quickly in the 20th century. "Cars replaced something that was in many ways far worse," says Donald Shoup of the University of California at Los Angeles. "But because of bad planning, they had unintended consequences." What might follow from AVs?

Shops that come to you

Cars transformed retailing, giving rise to suburban malls with lots of shops and plenty of parking. AVs, combined with the rise of e-commerce, could transform it again. "The Walmart of the future might be fleets of vehicles ready to drop off anything that you might get at a Walmart," says Peter Norton of the University of Virginia. Or you might order an AV to take you home from work, and arrange to have your groceries, or a meal, waiting for you when you climb aboard. And why should shops, restaurants or other facilities be fixed in place? Coffee shops or food stands could restock at a central depot and then migrate to business neighbourhoods in the morning and entertainment districts in the evening, suggests Chenoe Hart, an architectural designer at the University of California at Berkeley. Mobile shops selling items such as shoes, clothes or cosmetics could visit particular neighbourhoods on a regular schedule, or when hailed by a customer. "It gives us flexibility to reassign space," says Ms Hart.

Carmakers are experimenting with delivery vehicles that draw up outside a customer's home, announce their arrival by text message and allow items to be retrieved from a locked compartment by entering a code. Low-cost deliveries using AVs could stimulate local production of all kinds of things, most notably food. Already, food-delivery services like UberEats, Deliveroo, Seamless and GrubHub have given rise to "ghost restaurants" that produce food for delivery only, centralising food production in a few kitchens. Cheap autonomous deliveries could make this kind of model more widespread.

Another possibility, says Johann Jungwirth of Volkswagen, is that restaurants or retailers might cover the cost of travel to encourage customers to visit them. Fancy restaurants might lay on luxury AVs to ferry sozzled customers home, as part of the cost of a meal. Retailers could offer to pay for shoppers' rides. Ride-hailing networks have a lot of customer data that could be used to target in-vehicle advertising. Hail an AV to go to one shop or restaurant, and you might see ads for a rival. Riders may be offered cheaper rides with ads or more expensive ones without them.

Self-driving vehicles could also deliver other services, letting you work out with your personal trainer on the way to the office or summon a hairdresser to your home. Toyota's e-Palette vehicles are boxes on wheels in different sizes that can be kitted out as mobile shops, offices or beauty salons. Moreover, AVs could give rise to new kinds of social activities, just as cars provided teenagers with new social opportunities. Ride-hailing networks might group together people with similar interests or friends in common when assigning rides. Or they might work with a dating app, pairing people up with a potential match when they take a ride. AVs might also function as mobile party venues, or double as sleeping pods on long trips, offering an alternative to hotels and low-cost airlines.

A watchful eye

What unintended consequences might there be? One much-heralded benefit of AVs is that they will offer freedom and independence to people who cannot drive cars: the very old, the very young and the disabled. Such vehicles are already ferrying around people in retirement communities, and one of Google's videos shows a blind man doing errands in an autonomous car. But AVs could also encroach on freedom by invading people's privacy. Robotaxi operators will chronicle their riders' every move, so they will end up knowing a great deal about them. Some taxis already record riders for security reasons; robotaxis will surely surveil both their passengers and their surroundings to protect themselves. Police investigating a crime will ask AVs in the vicinity what they saw.

If people no longer drive cars, one consequence may be new forms of segregation, notes Ms Hart. Access to some places may be restricted to certain riders or robotaxi networks, just as some online services are "walled gardens" or cannot be accessed on all devices. She thinks there may be a need for a physical equivalent of "network neutrality" rules, to ensure that all locations are equally accessible to all AVs. In authoritarian societies, AVs could be a powerful tool of social control.

AVs could also trigger a shortage of organ donors (many of whom are young people killed in car accidents) and a drop in smoking (more than half of all tobacco sales in America are made at petrol stations, which will vanish, notes Mr Evans). And if cars are no longer symbols of independence and self-definition for the young, other things will have to take their place. Like cars before them, AVs will change the texture of everyday life. ■

SPECIAL REPORT
AUTONOMOUS VEHICLES

Implications for policymakers

Rules of the road

Smart regulation and smart technology must go hand in hand

REGULATING A COMPLEX new technology is hard, particularly if it is evolving rapidly. With autonomous vehicles just around the corner, what can policymakers do to ensure that they arrive safely and smoothly and deliver on their promise?

The immediate goal is to make sure that AVs are safe without inhibiting innovation. In America, experimental AVs are allowed on the roads in many states as long as the companies operating them accept legal liability. Chris Urmson of Aurora says American regulators have got things right, working closely with AV firms and issuing guidelines rather than strict rules that might hamstring the industry. "It's important that we don't leap to regulation before we actually have something to regulate," he says.

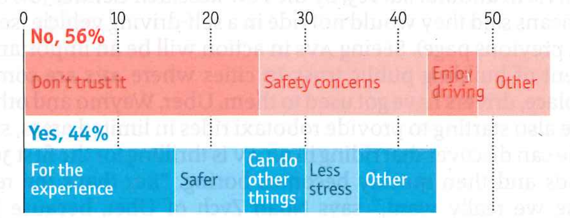
At the other end of the spectrum, Singapore's government has taken the most hands-on approach to preparing for AVs, says Karl Iagnemma of nuTonomy, an AV startup that has tested vehicles in the city-state. For example, it has introduced a "driving test" that AVs must pass before they can go on the road. This does not guarantee safety but sets a minimum standard. The city of Boston has done something similar, requiring AVs to be tested in a small region before roaming more widely.

Elsewhere, regulators have permitted limited testing on public roads but want to see more evidence that the vehicles are safe before going further, says Takao Asami of the Renault-Nissan-Mitsubishi alliance. "Simple accumulation of mileage will never prove that the vehicle is safe," he says. Instead, regulators are talking to carmakers and technology firms to develop new safety standards. Marten Levenstam, head of product strategy at Volvo, likens the process to that of developing a new drug. First you show in the laboratory that it might work; then you run clinical trials in which you carefully test its safety and efficacy in real patients; and if they are successful, you ask for regulatory approval to make the drug generally available. On this analogy, autonomous cars are currently at the clinical-trial stage, without final approval as yet.

What form would that approval take? Eventually, it will mean formal certification of vehicles capable of operating fully autonomously, so they can be offered for sale. But initial approval is likely to be granted to operators of specific robotaxi fleets, rather than vendors of particular vehicles, suggests Mr Levenstam, because fleet operators will monitor all vehicles closely to ▸▸

Belt up

Would you want to ride in a driverless vehicle?
US respondents, 2017, %



Source: Pew Research Centre

Cities for people, not cars

ensure and maintain safety. Even this will be a calculated risk. It is not possible to prove that a new drug is entirely safe, but the risk is worth taking because of the benefits the drug provides. It will be the same for AVs, he suggests. After all, the status quo of human-driven vehicles is hardly risk-free.

Mr Asami draws another analogy, with aviation. "Black box" data recorders and careful testing have enabled air transport to evolve, despite crashes, because passengers know safety is taken seriously. In fact, America's National Transportation Safety Board (NTSB) has started applying its aviation expertise to autonomous vehicles. In many ways AVs are more complex than aircraft, says Deborah Bruce of the NTSB, because they are closely surrounded by other things that move in unpredictable ways.

But medicine and aviation have global (or at least regional) regulatory standards, whereas AVs do not. The current patchwork of regulation will have to be simplified if the technology is to be widely deployed. "Uniformity is the friend of scalability," says Mr Iagnemma. Questions of insurance and liability will also have to be worked out. Amnon Shashua of Mobileye worries that because of today's regulatory uncertainty, fatal accidents involving fully autonomous vehicles could plunge the industry into legal limbo, or kill it altogether. He has proposed a set of rules that define how a car should respond in all 37 scenarios in the 6m-entry accident database maintained by NHTSA, America's car-safety regulator, and would like to see these rules adopted as an open industry standard. That would absolve carmakers from making implicit ethical choices in their software while leaving room for innovation in other areas. Mr Iagnemma thinks it is a good start. Without such standards, he says, every company will develop its own way of translating the rules of the road, devised for humans, into a code that can be followed by machines.

Political potholes ahead

The risk of a backlash seems real enough. A survey by Advocates for Highway and Auto Safety, a consumer lobby, found that 64% of Americans were worried about sharing the road with AVs. In another survey, by the Pew Research Centre, 56% of Americans said they would not ride in a self-driving vehicle (see chart, previous page). Seeing AVs in action will be an important element of building public trust. In cities where AVs are commonplace, drivers have got used to them. Uber, Waymo and others are also starting to provide robotaxi rides in limited areas, so people can discover that riding in an AV is thrilling for the first 30 seconds and then quickly becomes boring. "But that's the response we really want," says Noah Zych of Uber, because it means riders feel safe.

Assuming that AVs can be shown to be safe, regulators will face a second challenge: setting the rules around how and where they operate, and how they relate to other forms of transport. Fine-tuning of pricing will, in theory, let planners control congestion and promote equal access to mobility.

Governments wishing to encourage the adoption of robotaxi services could go further, restricting the use of private cars (Gothenburg, London, Milan, Singapore and Stockholm already have congestion charges of various kinds) or banning them from some areas. That might be unpopular, and not just with car-owners. "I think there will be some real resistance to measures that compel people to use autonomous vehicles," says Peter Norton of the University of Virginia. AVs could be seen as an Orwellian technology, an instrument of surveillance and social control.

Protesters might object by standing in front of AVs and blocking traffic. That could lead to calls for AV lanes to be fenced off, "thus making city streets even more inhospitable to non-motorists than they already are", says Brian Ladd, author of "Autophobia", a history of opposition to cars. But an unregulated introduction of robotaxis could also cause problems. Rival fleet operators might flood the roads with vehicles offering cut-price rides, making congestion worse.

Choices about transport and pricing are inescapably political in nature. How cities deal with them will depend on both economics and political dynamics, notes Justin Erlich of Uber. "We should be exploring lots of different policies in lots of different cities," he says. Meanwhile, two principles can help.

The first is to consider AVs in the context of the wider transport system, and be clear about what role they are expected to play. AVs might be deployed as the primary means of transport in a particular area; or they could be used in "first mile, last mile" mode to ferry people to and from railway stations, filling mobility gaps and complementing other forms of transport.

The second principle is to be mindful of the balance of freedoms. AVs can potentially free people from driving, congestion, pollution and parking—but in return may require them to give up some other freedoms, such as the ability to take their own vehicle anywhere. In liberal countries, AVs will be accepted only if people feel that they enhance freedom rather than reduce it.

A century ago cars raised fundamental questions about personal autonomy, freedom of choice and mobility. AVs will do the same again. But this time around, with the benefit of hindsight, there is a chance that they will be seen not simply as a new form of transport but as a technology with far-reaching social and economic implications. Driverless cars present an opportunity to forge a new and better trade-off between personal mobility and societal impact. But AVs will deliver on their promise only if policymakers—like passengers climbing into a robotaxi—are absolutely clear about where they want to end up. ■

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