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 xom 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 Pitts- burg 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.

Automobiles 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 identifiable by the clusters of sensors on their roofs. Uber’s robotaxi 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 2023 using autonomous Chevrolet 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.
Recent progress in computer vision and other machine-learning systems is one reason. Tech folk from chipmakers to software firms see AIs as a lucrative new market for their products. Within the automotive industry, the rise of Uber and other ride-sharing services caused a "massive shift in perception around 2012," says Sebastian Thrun, a pioneer of AI at Stanford who led the development of Google's first self-driving car. Carmakers realized that they needed to take AIs seriously—because they will redefine the industry.

The combination of autonomy and ride-sharing, together with a switch to electric vehicles, seems likely to undermine the logic of car ownership for many people. Ride-sharing services in the rich world currently cost around $2.50 per mile, compared with about $2.50 per mile to own and operate a private car (see chart). But the driver accounts for about 60% of the cost of ride-sharing. Uber, an investment bank, reckons that autonomy, competition, and electrification (which makes cars more expensive to buy but much cheaper to run) will cut the cost of ride-sharing by 70%, to about $0.50 per mile. So a typical Western household, driving 20,000 miles a year, could ditch its car, use robotaxis and save $3,000 a year. And there are other advantages, explains Mr Thrun: "You don't have to look for parking, and you can ride in the car.""  

"Once the car becomes autonomous, the relevance of car ownership drops materially," says David Lesbire of UBS. His firm predicts that robotaxis will take off rapidly after 2020, with 80% of people using them in cities, where available, by 2025; 85%, 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 cars, the fraction of autonomous vehicles will be shared broadly, says Nikolaus Lang of ecug. Globally, that "will revolutionise" (created by cognitive tech) the automotive industry, he also adds. Car-sharing service. Volkswagen, Europe's biggest carmaker, has struck deal with Audi, an AI startup founded by veterans of Google, Uber and Tesla. And so on.  

In short, the teutonic plates of technology and carmaking are colliding, heralding a carquake. This seismic shift will transform both industries, and its aftereffects will be felt far and wide: AI will be transformative a technology as the smartphones. 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 in traffic and the space wasted on parking. In urban planning, AVs provide "a great opportunity to address a lot of problems," says Joel Kocken, an urban-studies expert at Chapman University in Orange, California. "If the 21st 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 led to human suffering, AVs are raising new concerns about safety, cyber-security, liability and inequality.  

"Autonomous vehicle will create a Pandemonium's house of untroubled 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 "cerebral", notes Mr Norton. This special report will examine what technology is needed to make full autonomy possible. 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 re-shape cities? And what lessons does the rise of the car in the 20th century hold for driverless vehicles in the next?  

Ride-sharing

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Source: Press reports; Bloomberg

Designated driver

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Private car: Typical Uber fare

Ride-sharing, electric: Typical cost

Source: Uber

Making vehicles drive themselves is hard, but getting easier

The modern automotive era began with a competition. In the early 20th century, there was a huge amount of 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, was a blizzard of crowds of 100,000 as 21 contestants set out from Paris. Only two vehicles stayed the course; the way, seven dogs were run over and one cyclist was injured. The clear winner was not a direct competitor 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 internal combustion engines 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 2018, it was a contest to discover the best vehicle without a driver. It was organized by DARPA, America's main military-research agency, and required driverless vehicles to navigate a 3.5-mile road course. A total of 19 teams qualified, but after pre-contest trials and mishaps only 13 vehicles crossed the starting line. Amid mechanical failures, two cars failed to turn and none of them made it to the finish. Carnegie Mellon's Sandstorm, the vehicle that did best, travelled a 5.4 miles before getting stuck; as it tried to free itself, in front wheels caught fire.

It seemed that DARPA had set the bar too high. Yet when it held another competition in October 2018, five of the 21 participants had reached the finish line. The $1 million grand prize went to University of Michigan. In just 18 months, autonomous driving had gone from hopeless to feasible. In a third DARPA contest, in November 2019, vehicles had to complete tasks in a simulated urban environment, coping with road signs, traffic signals and other vehicles. Six out of a teams completed this much more-complex challenge.
the 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, allowed them to reveal when the road was 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 “flock learn- ing.” that gives an edge to first movers with thousands or millions of kilometers 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 in a particular challenge. lidar systems must be carefully tuned to ignore falling snow, and accumulations of snow on the road can mislead maps and models.

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 sun- shine and regular grid system, is a popular place to test avs. pitts- burgh is considered trickier because of its harsher climate. 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 a wider range of situations more often, and thus learn faster.

when an av gets confused and does not know how to re- act, 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 is the key metric of how the autonomous driving develop- ers compensate (see chart). disengagements are best seen not as failures but as learning experiences that help avs systems improve. sen- sor data recorded in the lead-up to a disengagement can then be tested in simulation. “we can play it back again and again, vary the scenario and see the distribution of outcomes,” says mi zy. the im- proved software is then rolled out in real cars.

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 on the way to deliver a truck on a two-lane road with a solid line down the middle, says christophe sapet of navvy, a maker of autonomous delivery vans. 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 split. but navvy’s avs are designed to keep a remote operational center, where a human operator can see live feeds from their cameras. rathen than controlling such a vehicle remotely, the operator gives it temporary permission to cross the white line when its

the public seems concerned mainly about two potential risks associated with avs: ethical dilemmas and cyber-attacks.

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 pay a $100,000 fee. but for now, most vehicles will ini- tially be offered for sale not to private owners but to robotaxi- operators. from GM to ford, carmakers are eager to release a large enough fleet to prove that self-driving cars are cheaper and more efficient than human-driven vehicles, and thus generating revenue, throughout the day, whereas priv- ate cars are used only during the day, when people need to get to work.

second, getting avs to work safely and reliably is much easi- er if their geographical range is limited to places that have been mapped in fine detail, such as city centers. so your first ride in an av will be in a vehicle you hail using an app, not one you own.

waysmo, alpaha’s av effort, is testing a robotaxi service in champaign, a suburb of chicago, with the aim of launching a commer- cial service later this year. uber is operating driverless taxis in parts of phoenix and pittsburgh; users who hail a ride may find themselves in a car that is controlled by a software engineer. another system, called urban moto, is being developed by an engineer (uber gives riders the option to use an ordinary car if they prefer). in san francisco, a robotaxi service in the village, a retirement community in san jose, and is expanding to a second location, in florida. navya, a french startup, is operating a light-rail autonomous shuttle bus in downtown las vegas, with three stops along a 0.6-mile route. it also has partnerships with cities around the world, as does easyrider, a rival french firm. large-scale de- ployments of avs are most likely to start with geofenced robo- taxi services in parts of cities such as singapore or dubai, and then expand over several years, predicts nikolaus lang of acco.

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 robotic cars in urban areas might encourage many young urban- ities, who are already going off car ownership anyway, to aban- don it altogether. the combination of ride-hailing and autono- mous-driving technology combines carmakers with “the most profound challenge to our business models in a century,” de- clares a recent report from acco. that is why carmakers are now piling into ride-hailing and car-sharing services and pushing on with their own av programs. in an autonomous future where ownership is optional, they need to be selling rides, not cars.

car shift factors offer a big opportunity. the car mar- ket is worth around $1 trillion globally, whereas for personal transport is worth as much as $10 trillion, according to mor- gan 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 allow others to partner for ride-hailing operators and changing them by the mile. some will even make “white label” fleets branded with the name of a city or a ride-hailing network, rather than their own brand.

robotaxi fleets running around the clock will generate pre- dictable yields that can be leveraged, turning themselves into asset managers for such fleets would be a logical step for carmakers, whose financial armes are already involved in fleet management, such as car subscription.

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. another option is the selling plan offers a certain amount of calls, texts and data.

one big question is the effect on avs on the number of vehicles sold world- wide. in 2019, there were around 80 million. since most cars sit unused 95% of the time, savings from having autonomous vehicles that oper- ate around the clock could greatly reduce the number of vehicles on the road. the rave research project estimates that will halve by 2050 (see chart, next page). but if robotaxi fleets are used just 7% of the time, they will need to be replaced far more often, says john jungwirth, chief digital officer of navya, because “the projected lifespan of vehicles requires modifications to their present roles that could enable the autonomous cars to be retrofitted for use, for example, in ride-hailing services, or to allow for better use of space and road capacity.”
> the number of new vehicles needed each year will rise. Making vehicles reliably large in quantities is hard, as Tesla’s production problems have shown. “The core expertise that we’ve had for decades is excellent manufacturing,” says Penzi Panditkuthina, head of product planning for the European arm of Nissan. “It’s a huge investment to buy the robots, being a certifier and there will still be a big business—just a different one from what it is today. After 150 years making hardware, says ltd Jungwirth, “we need to take software and services just as seriously.” That requires taking on new staff, retaining, acquisitions and partnerships. AVs will also be the first of many electric vehicles, which have fewer components and need fewer assembly workers.

Form follows function

It will not just be carmakers that change shape; we will change cars. Just as early “horseless carriages” resembled horse-drawn carriages, without the borse, the most autonomous vehicles today are ordinary cars, retrotitled 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 Ford Neoverse are two examples of each other. Future AVs may need to allow for some physical separation of passengers to encourage people to share vehicles with strangers, says Kad lemmero of nuvum, while families might have a different vehicle that lets everyone sit together.

All this is bad 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 robotics could hit them hard. Repair shops and part suppliers could also suffer, assuming AVs reduce the number of car accidents. Already, some produce 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. Health-care 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 those might be xedined rather than abolished. Delivery drivers could be employed to manhandle large packages into customers’ homes. Truck drivers might become oversees of platoons of vehicles travelling on highways. 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.

Decommission charge

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<th>Number of urban vehicles worldwide, bn</th>
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Urban planning

The new autopia

How autonomous vehicles will reshape cities

MODERN CITIES, PARTICULARLY in America, are habitats for cars, a much asymptotic, devolving 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 mandatoory parking requirements reshaped cities. Now AVs promise to transform them once again, undermining many car-centric assumpions 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 urban 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 robotics could increase vehicle occupancy rates, reducing the number of vehi- cles needed to move people around and easing congestion. But low-cost robotics might also encourage more people to take more trips—the familiar problem of "induced demand" when the road travel is cheap and easy. The roads could also fill up with au-tonomous delivery vehicles with nobody on board. The night- time 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 city planning can keep roads and sides rid of be able to prevent that. Some cities are al already have congestion-charging schemes of various kinds, or rules to encourage vehicle-sharing, such as dedicated car shar- ing 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 min- imise congestion. “It will be that interplay that ensures we don’t end up with highly congested roads,” says Justin Etich of UBC.

What about the impact on public transport? A study by ic Davids 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 pub- lic 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 robotics will work best in dense urban centers, says Mr Riggs, so “we could see social-equity implications around the fringes of cities.” But again, there is also a roster sce- nario. Using AVs for the “last mile” to move people to and from railway stations could make public transport move more viably in less densely populated areas. Some cities might also operate their own robotics fleets, or subsidise rides in poor neighbourhoods using toll revenues collected in rich ones.

The emergence of AVs helpfully coincides with a change in the structure of cities, says Rhomo Ang, an urban studies ex- pert 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, AVs are mov- ing 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 Ameri- can city are outside walking distance, leaving some walkable Asian cit- ies with dense public-transact networks this de-centralisation is easier to cope with, but retrofitting the necessary infrastructure on existing Canadian cities would be too expensive. “American cities need door-to-door transport systems to get to work, and driver- less cars will play that role,” says Mr Ang. Robotaxis hailing on demand promise to be a lot more efficient than private- ly 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 ca- reer 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 cit- ies as some of the space currently used for parking is reallocated to housing. New high-rise buildings could be built with pick-up and drop-off zones for ride-hailing vehicles, and fewer parking spaces. On the other hand, AVs could also encour- age sprawl by making long commutes more acceptable, because riders will be able to work or even sleep on the move. “The big- east negative of suburban living is the driving and the amount of space that has to be devoted to it,” says Joel Rotkin of Chap- man 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

In the past, new kinds of suburbs, ush- ing the 20th-century dream of garden cities. “Over the last 100 years our landscape has been drastically altered by the automo- bile,” says Mr Berger. With AVs, “all the land we’ve given to the automobile can be put back into landscape and ecological func- tions. By doing away with roads, you can turn one-lane roads that loop through neighbourhoods, the area of paved surface can be reduced by 50%, he calculates. That means more space on greenery, more wildlife and better water retention, reducing the risk of flooding in the long term. And the new AVs could even use fu- curage to have enough space to generate their own solar power or grow their own food.

Using AVs for the “last mile” to move people to and from railway stations could make public transport move more viably in less densely populated areas.
Foreseen and unforeseen consequences

ROAD TRIPS: DRIVEBOUGHTS, Shopping malls. Free cars. Car share. Road rage. Cars changed the world in all sorts of unforeseen ways. They gained 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 1.3 million people die in such accidents each year, according to the WHO; it is the leading cause of death among those aged 25–29. Another 200,000–500,000 people are injured. Most accidents occur in developing countries, where the arrival of autonomous vehicles is still some way off. But if the software could be advanced even by a single year, “that’s 200,000 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 belt 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 are driven amiles on public roads. The only accidents they have been involved in while driving automatically were caused by humans in other vehicles. AVs have superior 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 risk

> 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.

> Experimenting with delivery vehicles that drew upside down 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. A local bakery, for instance, could use an AV to deliver bread to local students and freshly baked muffins to the local high school. Seamless and GrabHub have given rise to “ghost restaurants” that cook in the back of cabs. AVs could centralise food production in a few kitchens. Cheap autonomous deliveries could make this kind of model much more widespread.

> Climatologists and says Johann Jungfleisch of Volkswagen, is that restaurants or retailers might cover the cost of travel to enrol customers to visit them. Fancy restaurants might lay on a free AV to ferry seeded 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 get a discount on the next one.

> Ride-sharing services like UberEats. Deliveroo, Seemaster and GrubHub have given rise to “ghost restaurants” that cook in the back of cabs. AVs could centralise food production in a few kitchens. Cheap autonomous deliveries could make this kind of model much more widespread.

>EVs and autonomous cars could make cities much more livable, reducing pollution and congestion, says Takeo Kanai of Nissan, an AV startup that has tested vehicles in the city-state. For example, saying we’re in 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.

> Regulations 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 Alliance. “A rule that would say that a million miles 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, likes the process that is like that of developing a new drug. First you show how safe it is in controlled clinical trials in which you carefully test its safety and efficiency 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 available.

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 robotic fleets, rather than vendors of particular vehicles, suggests Mr Levenstam, because fleet operators will monitor all vehicles closely to

Goodbye to all that

A different world

Society

Foreseen and unforeseen consequences

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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-entrant 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 robotaxis 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 robotaxis 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 are as free as ever, 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 robotaxis—are absolutely clear about where they want to end up.