FEATURES

NOT SO FAST

We can't even agree on what autonomous vehicles are, much less how they will affect our lives

By **Jeffrey Mervis**

ILLUSTRATION: EMILIANO PONZI

The automakers and high-tech companies spending billions of dollars on developing self-driving cars and trucks tout the idea that autonomous vehicles (AVs) will help create a safer, cleaner, and more mobile society. Politicians aren't far behind in their enthusiasm for the new technology.

"This is probably the biggest thing to hit the auto industry since the first car came off the assembly line," Senator Gary Peters (D–MI) told a cheering audience of researchers and executives at a recent computing conference in Washington, D.C. "It will not only completely revolutionize the way we get around, but [AVs] also have the potential to save hundreds of thousands of lives each year."

Such predictions, however, turn out to be based on surprisingly little research. While developers amass data on the sensors and algorithms that allow cars to drive themselves, research on the social, economic, and environmental effects of AVs is sparse. Truly autonomous driving is still decades away, according to most transportation experts. And because it's hard to study something that doesn't yet exist, the void has been filled by speculation—and starkly contrasting visions of the future. "The current conversation ... falls into what I call the utopian and dystopian views," says Susan Shaheen, co-director of the Transportation Sustainability Research Center at the University of California (UC), Berkeley.

In the utopian view, she says, fleets of cheap, accessible AVs offer rides at the tap of a screen. Their ubiquity expands transportation options for everyone. Once AVs are commonplace, traffic accidents become a thing of the past, and enlightened government regulatory policies result in fewer traffic jams and parking problems, and less urban sprawl. Fleets of electric-powered AVs shrink fossil fuel consumption and reduce air pollution. Commutes become stress-free and more productive, as former drivers can now work, read, or knit while being whisked to their destinations.

Still, a handful of cleverly designed experiments have given scientists insights into how AVs could change how we live, work, and play.

WHEN WILL WE HAVE TRUE AVS?

First, some basic terminology. Yes, an AV is a car that drives itself. But automotive engineers say that answer is imprecise and leaves the public confused.

For engineers, an AV is a car that takes you where you want to go, at any time and under any drivable condition, without any human intervention. You give it your destination, and off it goes—to New York City or the Gobi Desert.

That robust capability is at the top of a six-point scale of automation (see box, above) devised by the Society of Automotive Engineers and adopted by the U.S. National Highway Traffic Safety Administration (NHTSA) in Washington, D.C., as the government's template. Technically, anything below level five is not an AV. (Level-zero cars are what your parents drove, and most cars on the road today operate at level one.)

So far, nobody is close to deploying a level-five vehicle. The cars Uber has tested on the streets of Pittsburgh, Pennsylvania, and Google's experimental fleet, for example, operate under tightly controlled conditions. But you wouldn't know it from the torrent of press releases from companies involved in AV development.

"Any level of automated driving gets described by the media as driverless," says Steven Shladover, a transportation engineer at the California Partners for Advanced Transportation Technology program in Richmond. "Companies have gotten very good at crafting statements [about automation technologies] that will be presented in the most positive light," he says.

Companies have good reason for painting the rosiest scenario for their technology, Shladover says. "Nobody wants to appear to be lagging behind the technology of a competitor because it could hurt sales, their ability to recruit top talent, or even affect their stock price," he says.

As a result, it's easy for the public to overestimate the capabilities of existing technology. In a fatal crash involving a Tesla Model S and a semitrailer in May 2016, the driver was using what Tesla describes as the car's "autopilot" features—essentially an advanced cruise control system that can adjust the car's speed to sync with other vehicles and keep the car within its lane. That fits the definition of a level-two vehicle, which means the driver is still in charge. But he wasn't able to react in time when the car failed to detect the semi.

Shladover believes AV companies need to be much clearer about the "operational design" of their vehicles—in other words, the specific set of conditions under which the cars can function without a driver's assistance. "But most of the time they won't say, or they don't even know themselves," he says.

The six levels of autonomy were intended to tell the public where things now stand and where the technology is headed. But such a classification system implies that companies will make incremental and steady progress in reaching higher levels: initially rolling out cars at level three, then a few years later at level four, and finally at level five.

But progress will likely be anything but steady. Level three, for example, signifies that the car can drive itself under some conditions and will notify drivers when a po-

The six levels of auto autonomy

Transportation experts have developed six levels that describe autonomous vehicles. In general, a higher number means a more independent vehicle, with less for the human driver to do, thanks to more sophisticated sensors, cameras, and algorithms. We also assess the prospects for reaching each autonomy level.

LEVEL	ZERO	ONE	TWO	THREE	FOUR	FIVE
What the car does	Nothing	Accelerates, brakes, or steers	Accelerates, brakes, and steers	Assumes full control within narrow parameters, such as when driving on the freeway, but not during merges or exits	Everything, only under certain conditions (e.g. specific locations, speed, weather, time of day)	Everything—goes everywhere, any time, and under all conditions
What the driver does	Everything	Everything, but with some assistance	Remains in control, monitors and reacts to conditions	Must be capable of regaining control within 10–15 seconds	Nothing under certain conditions, but everything at other times	Nothing—and unable to assume control
Our take on the prospects	Your parents' car	Present fleet	Now in testing	Might never be deployed	Where the industry wants to be	Somewhere over the rainbow

GRAPHIC: K. SUTLIFF/*SCIENCE*

tential problem arises in enough time, say 15 seconds, to allow the human to regain control. But many engineers believe that such a smooth handoff is all but impossible because of myriad real-life scenarios, and because humans aren't very good at refocusing quickly once their minds are elsewhere. So many companies say they plan to skip level three and go directly to level four—vehicles that operate without any human intervention.

Even a level-four car, however, will operate autonomously only under certain conditions, say in good weather during the day, or on a road with controlled access. The technology for that capability already exists and "is trivially easy," notes Gill Pratt, CEO of the Toyota Research Institute in Palo Alto, California. The real challenge, says Pratt, a former academic and government program manager in robotics and intelligent systems, is developing a vehicle that can drive in "very difficult domains," such as rainy weather or crowded roads. That's level five, and Shladover, for one, says he wouldn't be surprised if it's 2075 before we get there.

HOW SAFE IS SAFE ENOUGH?

Policymakers assume that removing the human element will make driving vastly safer than it is now. It's an appealing idea: Worldwide, some 1.25 million people die in vehicular accidents each year, and many more sustain serious injuries.

Most experts believe AVs will greatly reduce that carnage once the technology is perfected and AVs make up the majority of vehicles on the highways. But that could take years, as manufacturers gain experience. In the meantime, policymakers must decide when it is safe enough to allow AVs on the road.

Congress is now considering legislation that would allow AV-makers to deploy the cars so long as they are deemed as safe as current vehicles. Even that is a high bar, Shladover notes. He has calculated that a fatal crash now occurs once every 3.3 million hours of vehicle travel; an automated system will need to be extremely reliable to beat that record.

What's more, the conventional wisdom holds that the public will be much less accepting of crashes caused by software glitches or malfunctioning hardware rather than human error. "Society now tolerates a significant amount of human error on our roads," Pratt told a congressional panel earlier this year. "We are, after all, only human."

Pratt believes that even cutting the number of annual fatalities in half—saving 18,000 lives in the United States, for example—would not be good enough for AVs to win the public's trust. Instead, he says, policymakers will need to "determine what constitutes a sufficient level of safety."

Some analysts believe that gradually deploying even imperfect AVs sooner rather than later could help win over the public and speed improvements. "Waiting for the cars to perform flawlessly is a clear example of the perfect being the enemy of the good," says Nidhi Kalra, a senior information scientist at RAND Corporation in San Francisco, California.

She and RAND's David Groves recently co-authored a study that urges the government to allow AVs on U.S. roads once they can achieve a 10% reduction in fatalities from current levels. Further improvements in safety, the authors assert, will occur more rapidly if the self-driving algorithms can learn from real-world driving rather than from computer simulations or endless trips around test tracks. Gradually introducing imperfect AVs by 2020 would save twice as many lives by 2070 than if the government waited until 2040 to allow the deployment of "almost perfect" AVs, they conclude. (Kalra acknowledges a personal stake in AVs: Her husband, Dave Ferguson, is cofounder of Nuro Inc., a machine-learning startup in San Francisco that would benefit from early AV deployment.)

A driverless shuttle began operating this fall at the University of Michigan's Mcity test facility in Ann Arbor.

That argument makes sense to Shladover, who says early deployment could help the industry overturn the conventional wisdom that AVs must never cause harm. "These machines will kill people," he asserts. "They will never be perfect. And it's going to take decades until they are 10 times safer."

WILL AVS LEAD TO MORE DRIVING?

Whether AVs will deliver utopia or dystopia depends in large part on their effect on current driving patterns. To get at the answer, Joan Walker, a transportation engineer at UC Berkeley, designed a clever experiment. Using an AV is like having your own chauffeur, she reasoned. So she gave 13 car owners in the San Francisco Bay area the use of a chauffeur-driven car for up to 60 hours over 1 week, then tracked their travel habits.

"The idea was to put people in a situation like what the future may be," says Walker, who worked with researchers from three other universities. "That is, you can send the car on errands, and you don't have to worry about driving or parking."

The subjects, who had to pay for gas and maintenance but not for the driver, were drawn from three demographic cohorts—millennials, families, and retirees. The study compared their use of the chauffeured car with how they drove their own cars in the week before and after the experiment.

The results suggest that a world with AVs will have more traffic. Overall, the 13 subjects logged 76% more miles, took longer trips, and traveled more at night than they normally would. The retirees more than tripled their evening driving and nearly doubled the number of longer trips. Three-fourths of the supposedly car-shunning millennials clocked more miles. In addition, one-fifth of all trips had no passengers. Subjects with children were especially likely to send the chauffeur to pick up friends and family as they sat in their offices.

Walker readily admits to the study's limitations, including a small sample size. (She has funding to repeat the study next summer on a larger scale.) Even so, she thinks the experiment and subsequent interviews with every participant shed new light on how people might use AVs. For example, in contrast to conventional wisdom that older people would be slower to embrace the new technology, Walker says, "The retirees were really excited about AVs. They see their declining mobility and they are like, 'I want this to be available now.'"

That sentiment doesn't surprise Pratt, who hopes AVs can end a heart-wrenching generational conflict. "When you get older, someone takes away your car keys," he says. "My sister and I had to do that with our dad, and it's a terrible thing."

WILL YOUR CAR BECOME YOUR OFFICE?

One of the biggest selling points for AVs is that former drivers will be able to use their travel time more efficiently, for work or leisure. But motion sickness might mar that idealized vision, says psychologist Michael Sivak of the University of Michigan in Ann Arbor.

Sivak, founder of an industry-funded transportation research consortium, says his team wanted to examine whether the productivity benefits really exist. And soon, he says, they realized that, "by mov-

PHOTO: UNIVERSITY OF MICHIGAN

ing from being a driver to a passenger, you are increasing your susceptibility to motion sickness because the visual and vestibular inputs do not match."

Sure enough, when Sivak and his colleague Brandon Schoettle asked 3200 adults in five countries what they would do in an AV, more than one-third named activities—such as reading, using their smartphones, or working on a laptop—that might make them sick. Using those answers as a baseline, they calculated that up to 12% of AV users were likely to experience moderate or severe problems. "Basically, we are saying that this is a potential problem, and that the automakers need to solve it," Sivak says.

Joseph Coughlin, director of the AgeLab at the Massachusetts Institute of Technology in Cambridge, predicts that companies will have a powerful incentive to do so. "The most valuable thing coming from AV technology is trapped attention," he says. "If I'm Amazon and I have your undivided attention for an hour, I will figure out a way to eliminate motion sickness and remove all the other obstacles to enjoying the ride so that I can sell you things."

WILL YOU BUY YOUR OWN AV?

Since the Model T, most people have owned the cars they ride in. Many see their car as an extension of themselves, if not a statement of who they are. But some experts predict an end to that relationship, pointing to declining rates of car ownership among younger, urban dwellers and a smaller percentage of young adults even bothering to get a driver's license. In a world filled with AVs, they speculate, people may be content to rely on someone else—a company, the government, or some public-private partnership—to provide the right car when they need it, rather than keeping multiple cars in their driveway at their beck and call.

Coughlin is betting that "we will probably never own an AV." But he says that doesn't mean everybody will receive the same level of service. The wealthy, he imagines, may choose to sign up for a platinum package that sends a luxury car to their home every morning. In contrast, those who must pinch their pennies could buy a monthly subscription that offers shared rides in a subcompact that will pick you up around the corner.

Ownership patterns could also be influenced by federal, state, and local policies. Last year, for example, Boston set safety, accessibility, and reliability as its top three transit goals for 2030. And although the plan doesn't specify which transit options people should use, says Kris Carter, a senior innovation officer for Boston Mayor Martin Walsh, "We hope for a shift away from vehicle ownership toward fleets, including an increase in AVs." Carter says the city hopes to encourage that shift through an assortment of government subsidies, tax incentives, and budget allocations.

Rural communities might go in a different direction. Government subsidies might be required to give residents of a sparsely populated area the same access to AVs that their urban neighbors enjoy, for example. And advocates for mass transit, bicycling, and carpooling might demand that AV fleets enhance, rather than compete against, such sustainable forms of transportation.

HOW WILL AVS BENEFIT COMPANIES?

Technologists see AVs as the next step in what's called "mobility as a service." That is what taxi fleets and ride-sharing services such as Uber and Lyft now offer. What is attracting AV investors is the huge payoff from removing the biggest cost of that service, namely, the person behind the wheel.

> ***"If I'm Amazon and I have your undivided attention for an hour, I will figure out a way to eliminate motion sickness ..."***
>
> **Joseph Coughlin**, Massachusetts Institute of Technology

"Sure, safety, access, and convenience are important," Pratt says. "But the reason there is so much money going into [AVs] is because of the potential cost savings from getting rid of the human driver. ... That's where the real money is going to be made."

The projections are staggering. Last month, for example, General Motors (GM) officials said the company hopes to begin deploying a fleet of autonomous taxis in large cities by 2019. That timetable, if met, would put it ahead of its competitors. But the real news came from its explanation of how this step could help GM's bottom line.

GM now sells its cars for an average of $30,000, and has a profit margin of 7.5%. But an AV that is part of a GM-owned fleet operating 24 hours a day, 7 days a week would generate revenues of "several hundreds of thousands of dollars" per car and profit margins of up to 30%, GM President Dan Ammann told an investors conference in San Francisco.

Under current practices, the drivers for ride-sharing companies keep about two-thirds of the revenue generated after paying the maintenance and operating costs of their car. Remove the driver, and the car owner—in this case, GM—gets to keep all the profits. GM officials say consumers will also benefit, predicting the current $1.50 per kilometer average cost of a ride will drop by more than half.

HOW WILL GOVERNMENT REGULATE AVS?

While the AV industry races to solve the technological challenges, company officials are casting a wary eye on government. They worry that any regulation tied to a specific technology will quickly become outdated and, thus, impede further innovation. They also warn that a "patchwork" of state and local laws and regulations could block them from operating in some markets and limit economies of scale.

"We have research labs in three states—California, Michigan, and Massachusetts—but we test primarily in Michigan because the rules are the easiest to deal with," Pratt says. "If we wanted to drive from Cambridge to Watertown [in Massachusetts] we'd have to apply to both towns for permission, and maybe even need an escort."

Federal lawmakers want to ease the way for AVs. Companion bills with broad bipartisan support, one passed by the House of Representatives (H.R. 3388) and the second moving through the Senate (S. 1885), would give companies a relatively free hand to test and deploy millions of experimental vehicles on U.S. roads. As Peters, the senator from Michigan, asked at the Washington, D.C., computing conference, "Why wouldn't we do everything we can to make that happen?"

Still, multiple layers of government bureaucracy will be a fact of life in the United States for the AV industry. The federal government and NHTSA are responsible for vehicle safety, but it's up to state and local jurisdictions to license the cars and lay down the rules of the road. And efforts to hasten the arrival of AVs could clash with attempts to address broader societal goals.

These scenarios provide researchers with plenty of fodder. And there are many more issues to explore. For example, Sivak's team has looked into public fears that terrorists might turn an AV into a weapon, as well as whether claims of greater fuel efficiency square with how people say they would use AVs. "As researchers, we want to first understand [the impact of AVs] and how they differ among various groups" before making any recommendations to policymakers, Shaheen says.

And what's her guess about whether AVs will sink or save us? "Personally, I don't think the future will be that black and white," she says. "There are too many variables, and so much diversity." ■

PHOTOS: (OPPOSITE PAGE) FORD MOTOR COMPANY

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