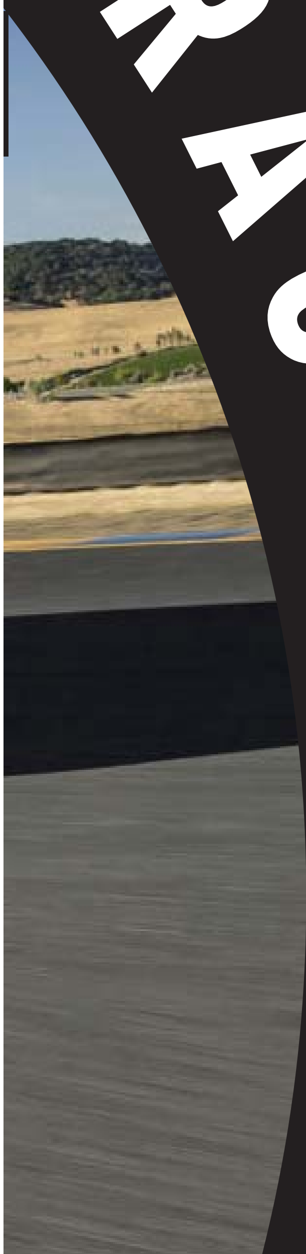
OFF TO THE

Who better to teach cars how to drive themselves than the professionals who race for a living?

HANDS FREE
Robby, an Audi RS7, is based on Stanford University research that applied the skills of race car drivers to computer-driven vehicles. It took only 2:01 minutes to complete the 2.5 mile Sonoma Raceway circuit.
Photo: Audi

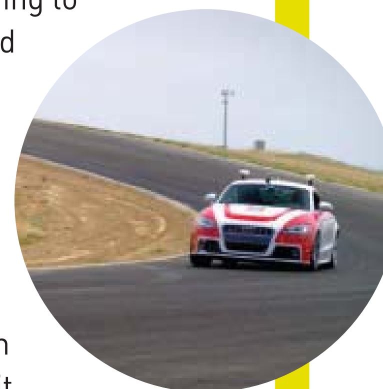


RACES

BY DAN FERBER

ON A FALL MORNING AT CALIFORNIA'S THUNDERHILL RACEWAY, David Vodden dons a white helmet and racing suit, straps into the driver's seat of an Audi TT sports car, revs his engine, and tears across the starting line.

Vodden, a longtime amateur racer who also happens to run the race track, roars around the curves, taking them on the inside again and again, trying to slice off some distance and outpace his opponent. But his opponent is relentless, almost robotic, in its tactics. On the long straightaway approaching the final turn, his opponent, also an Audi TT, tops 110 mph as it takes a commanding lead—which it holds through the final turn to the finish.



Just like that, Vodden became the first driver in history to lose a race to a car without a driver.

There was no shame in Vodden's loss. In fact, it was an engineering milestone. And in reality, the Audis racing each other were one and the same car. Their race was virtual, with animations of two runs superimposed on one another. After overcoming one engineering hurdle after another, the self-driving sports car, named Shelley, could finally keep up with a skilled amateur racer.

Despite its newfound racing prowess, the autonomous Audi, which was built by Stanford mechanical engineering professor Chris Gerdes, was not designed to win races at Le Mans, or even at Thunderhill Raceway, a curvy three-mile road course north of Sacramento. In designing Shelley, Gerdes and like-minded colleagues aimed instead for autonomous cars that can navigate traffic jams and make quick maneuvers to avoid accidents.

"The goal in my lab is to design self-driving cars

90% OF AUTO CRASHES INVOLVE DRIVER ERROR, A FEDERAL STUDY SAYS.

that handle emergencies even better than the very best human drivers," Gerdes said. "And the first step to doing that is to make sure they have phenomenal driving skills."

The stakes of such research are high—both in dollars and in human life. Of the 5.7 million motor vehicle accidents in the United States each year, 30,000 are fatal. What's more, 94 percent involve driver error, according to a three-year study by the National Highway Traffic Safety Administration.

Statistics like these have propelled Gerdes, and his counterparts at Google, Audi, Tesla, and other companies to build autonomous cars. "Just about every manufacturer is developing automated parking or driving or both," said Brad Stertz, communications lead for Audi's piloted driving project.

When they succeed, self-driving cars will handle emergencies better than you do.

RACING FOR SAFETY

The dream of self-driving cars dates back at least to 1939, when General Motors showcased the idea in its Futurama exhibit at the World's Fair in New York. But when Gerdes was growing up in Concord, N.C., in the shadow of Charlotte Motor Speedway, that dream was light years away.


FUTURAMA WORLD'S FAIR, 1939

As a kid, Gerdes dabbled in go-kart racing, but gravitated more towards math than motorsports. Math led to physics and engineering. "To me the magic of physics and engineering was that you could work out the mathematics and describe how things move," Gerdes said. "And cars are one of the most interesting things in terms of figuring out how they move."

As a graduate student at the University of California, Berkeley, in the early 1990s, Gerdes worked on a now-defunct U.S. Department of Transportation program to create automated highways on which closely spaced platoons of automated vehicles would draft each other. The lead cars would pull followers into their slipstreams, saving fuel and giving their drivers a break. He then worked at Daimler-Benz for three years, where he developed mathematical algorithms and computer simulations to model how the company's heavy trucks would maneuver on the road.

After joining Stanford as an assistant professor in 1998, Gerdes wanted to program cars to control themselves in an emergency. But after funders balked, he began working on automating vehicles for less dangerous situations. It took another decade before Gerdes could again pursue automation that might keep drivers safe when things go wrong—when they hit a patch of ice, for example, or when a deer darts into the road and they steer away too fast and lose control.

To make cars safer in such emergencies, Gerdes looked around for people who drove well, especially with their cars pushed to the limit. That led him to professional race car drivers.

Miles Collier, a Florida real estate baron and son of an auto racing pioneer, helped found an automotive research program at Stanford and also owns one of the world's greatest collections of vintage race cars. Collier let Gerdes's team record how the vintage cars handled, and introduced him to veteran race car drivers such as John Morton, Roger Mandeville, and Gunnar Jeannette.

As it happens, race car drivers don't drive like the rest of us. Most of us try to force our car to hew to the path we want it to drive. But race car drivers see driving as more of a dialogue.

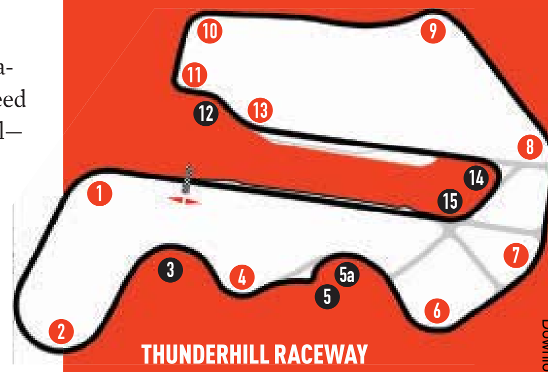
As they race, Gerdes said, "they're feeling out the capacity of the car and letting it reach its limit." When cornering, for example, they actually let the car sideslip a bit so they maintain as much speed as possible through the turn. They guide their car around the track rather than forcing it.

In an epiphany, Gerdes realized that if his team could figure out the underlying math, they could one day program a self-driving car to drive this way—to drive as well as the very best human drivers.

THE ROAD TO THUNDERHILL

A few years earlier, Gerdes had organized a brainstorming session with engineers from Audi and its parent company, Volkswagen, to come up with research ideas to push the capabilities of self-driving cars. The engineers, who met in San Francisco in late 2007, agreed that to make ordinary self-driving cars safer, it would be invaluable—not to mention cool—to build an autonomous race car.

Gerdes took on the task. Within 15 months, this time with Nissan's support, five Stanford engineering students on his team had designed and built a programmable self-driving, all-electric car. The car, named P1, had rear-wheel drive and a front-wheel steer-by-wire system, but it looked more like a dune buggy than a Chevy Volt or a Nissan Leaf. Yet despite its scraggly appearance, it did something no previous self-driving car could do. It drifted as it cornered with such control that it never spun out, just like a cornering race car driven to its limits by a pro.



MORE ON THE FLOOR

Racing with no driver takes high-speed computing, and Shelley is well equipped. The car's original processing system, which takes up most of the trunk, rapidly tracks and corrects its location by comparing data from its inertial measurement system with data from its GPS. The system must make these calculations fast enough to control the balance of the car as it approaches it's cornering limits during high speeds turns.

Photo: Gerdes Lab, Stanford University

In 2009, working with Audi engineers, Gerdes added sensors and extra computing power to an Audi TT that enabled it to drive itself. Over the next year, the autonomous car, now named Shelley, had zipped singlehandedly up switchback after switchback to the top of Colorado's 14,000-foot-high Pikes Peak, and sped to more than 130 mph on Utah's Bonneville Salt Flats.

Two years later, Gerdes approached Vodden about renting time at Thunderhill Raceway.

"They came into my office and saw all these trophies and pictures, and they were impressed that I was a real honest-to-gosh race car driver," Vodden said. "With my title of president and CEO, they didn't know I went out and crashed cars and ran into rivals and pushed them off the track and did all the things race car drivers do so well. They began to believe that I was good, and I was *not* going to correct them."

The Stanford team wanted to learn how experienced drivers think as they race, and asked Vodden if they could monitor the electrical activity of his brain. "They wanted a car to think like a race car driver," Vodden said. "They had me driving a car, put little electrodes in my brain, and interpreted them somehow."

The brain emits theta waves when it's working hard, especially at visual processing, and alpha waves when it's resting. By measuring the ratio of theta to alpha waves, Gerdes and his colleagues learned that Vodden and other experienced race car drivers don't have to think particularly hard when cornering on a track. Even as the car careens around a corner at the edge of its capabilities, a professional driver will calmly adjust, making quick changes to the steering, throttle, or brake to stay on the track.

PIERO TARUFFI

"It's extraordinary," Gerdes said. "They're concentrating on the other vehicles around them. Controlling the car has become automated."

SAFETY AT ANY SPEED

To design automated vehicles that drive as well as race car drivers, Gerdes also drew on a 1959 book he'd discovered by Piero Taruffi, an Italian Grand Prix champion.

In the 1950s, racing was extremely dangerous for drivers, and crashes at the track would occasionally take out groups of spectators as well. Taruffi led the fight for safety in the sport, even penning an article in the *Saturday Evening Post* titled "Stop Us Before We Kill Again."

Taruffi eventually earned a Ph.D. in industrial engineering at the University of Rome and wrote a classic book that discusses the physics of racing.

"Even though he wasn't going into any equations, you could see that the equations and the mathematics were part of his thinking," Gerdes said. "His insight was phenomenal. I don't think I've seen clearer explanations since that time."

Gerdes's team, like other autonomous car designers, had initially programmed their cars to compute and follow a particular path. On the streets and the freeways, that meant staying in lane, turning at the right place, and not driving off the road. For race car drivers, it meant finding the best path around the track—the best racing line.

Taruffi realized there was no single ideal racing line. Instead, the trick was to find a good line and drive it at the limits of the car. Human race car drivers use their brains, conditioned by years of experience, to calculate those lines. Computers directing autonomous cars would have to rely on math.

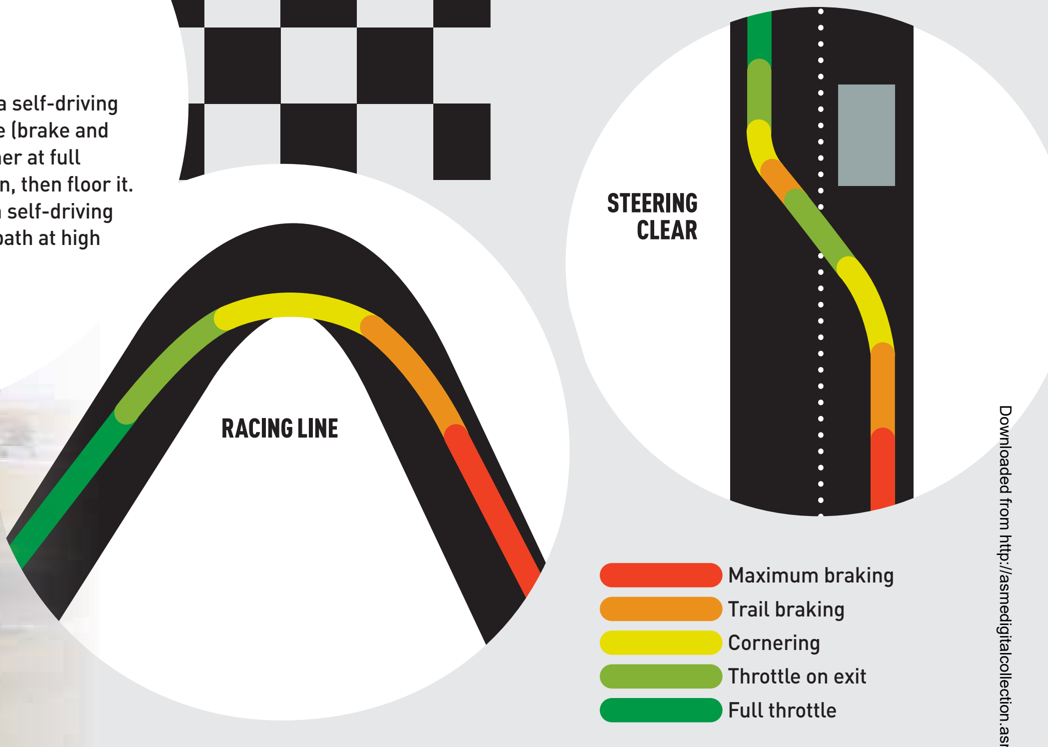
All cars have a limited amount of friction between their tires and the road. To win races, drivers need to make the most out of it. For this reason, they floor it on straights, brake hard at the last minute as they near a turn, ease up on the brake during the first half of the turn, release the brake entirely, and gradually step on the gas as they ease out of the turn and back to another straight.

In his book, Taruffi had drawn clear diagrams that explained how to break down racing lines into straights, arcs, and a curve representing how drivers steered into or out of turns. Inspired, Gerdes looked for a mathematical way to represent these three elements.

THEY TAUGHT THE CAR TO DRIVE LIKE A RACE CAR DRIVER— TO CALCULATE WHEN TO BRAKE BEFORE A TURN, HOW MUCH TO LET UP ON THE BRAKE ENTERING A TURN, HOW MUCH TO THROTTLE COMING OUT OF IT.

DODGING DISASTER

To navigate a racing turn, a self-driving car must brake, trail brake (brake and turn simultaneously), corner at full speed, throttle out of a turn, then floor it. Similar algorithms allow a self-driving car to drive an S-shaped path at high speed around an obstacle.



The straights and arcs were easy, but the transition curves posed a challenge. Eventually, Gerdes learned to represent those curves mathematically, using segments of a teardrop-shaped curve called a clothoid. Using those same three elements, he and former Stanford graduate student Paul Theodosis came up with an algorithm that represented a complicated racing line at Southern California's Laguna Seca raceway.

By programming Shelley with that algorithm, they taught the car to drive like a race car driver—to calculate when to brake before a turn, how much to let up on the brake entering a turn, how much to throttle coming out of it. And when they ran Shelley at Laguna Seca in a virtual race against driver Bruce Canepa, the world-record holder of the Pikes Peak Hill Climb, Shelley drove an aggressive racing line almost identical to Canepa's and drove it fast enough to give Canepa a run for his money, they reported at the ASME Dynamic Systems and Control Conference in 2012.

LESSONS FROM THE TRACK

Gerdes's team drew another lesson from the way race car drivers make the most of friction to maintain maximum speed on the track. "Their purpose in doing that is to be fast, but in fact the specifics are the same if you're trying to use all the friction between the tire and road to be safe," Gerdes said. And you might need every bit of friction if a mattress falls off the truck in front of you or a deer darts in front of your car.

To see if they could program Shelley to dodge such obstacles, Joe Funke, a graduate student in Gerdes's lab, derived an emergency lane change algorithm using the same underlying math the team had used at the race track. In tests at Thunderhill, Shelley calculated a new path on the fly and steered while easing off the brakes like a race car driver heading into a turn, shifting lanes smoothly and quickly.

The Stanford team borrowed yet another tactic that race car drivers use to avoid crashes. Say you're driving on a dry road and you hit a patch of ice, just as the car in front of you brakes hard. The lane to your left is open, so you steer left, but your rear end fishtails right. Race car drivers face the same risk as they corner. To control the car when they veer off course, they bend their path toward their desired racing line and return to it gradually.

Ordinary drivers face the same challenge during an emergency lane change. If you steer too abruptly, you could spin out. But if you read the situation and bend your path slowly into an adjacent lane, you can maintain control and avoid an accident. Last year, Gerdes, Funke, and two other team members used racing-derived algorithms to program another one of their vehicles, an all-electric rear-wheel drive car called X1, to do just that. When it had to, it quickly shifted two lanes over, swerving off course briefly, but adjusting.

Impressive for a car with no driver, but Gerdes wants to up the ante. So far, the team's autonomous cars have operated alone on tracks or roads. Now, Gerdes is ready to test them in traffic and on icy roads that will force Shelley to adapt driving tactics midstream.

Long before driverless cars cruise down our freeways while we text, surf, and relax, carmakers will quietly add more automatic safety functions to complement the active cruise and electronic stability controls that already partly automate our driving.

More than a few of those inventions might come by watching how experienced race car drivers fly around a track and incorporating their skills in autonomous systems.

As Gerdes told us, "We keep finding that the things that make human drivers faster are the same things that we need automated vehicles to do." **ME**

DAN FERBER is a journalist based in Milwaukee who writes about science, engineering, and technology. He is the co-author, with Paul Epstein, of *Changing Planet, Changing Health: How Climate Change Threatens Our Health and What We Can Do About It.*