# Autonomous Driving and Related Technologies

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## Abstract

We're in the middle of a rapid evolution of the way vehicles are operated on road. Thanks to innovations like sensor technology, data analysis, and artificial intelligence, a growing number of companies from outside the traditional automobile industry join the race of building ultimately autonomous vehicles. In this paper, we conduct a study on self-driving technology. Autonomous cars offer many benefits. The primary benefit is that they reduce accidents and save lives. There has been a long history of developing self-driving cars, from Stanford Cart in 1961 to Tesla and Google at present. The differences between Tesla and Google are mainly in two areas, computer vision technology and human car control. Self-driving is challenging and requires a wide range of technologies, including learning the environment, tracking objects, localization, path planning,

and control. We illustrate finding lane lines with computer vision and predicting the location of other vehicles using Kalman filters.

## I. Introduction

Over the last three decades, we have seen increasing research interests and efforts in both academia and industry towards developing self-driving vehicle technology. These developments are accelerating thanks to recent advances in sensing and computing technology. Public attitudes on autonomous driving have changed from “maybe possible” to “definitely possible”, and to “inevitable.” Every significant automaker is pursuing this technology and eager to rebrand itself as an autonomous mobility provider.

Out of many potentials, safety is the primary reason for developing self-driving cars. Many thousands of people die in motor vehicle crashes every year in the United States. The National Safety Council (NSC) estimated automotive fatalities topped 40,000 in 2017 [1]. Recent National Highway Traffic Safety Administration (NHTSA) research shows that approximately 94 percent of accidents are caused by human error, including around 40 percent involving intoxicated drivers and 10 percent distracted drivers [2].

Self-driving vehicles could dramatically reduce the number of accidents. The sensors on a self-driving car are always observing. They are not affected by the state of the driver (fatigue, emotion, etc.) and can scan in multiple directions simultaneously. The software on an autonomous vehicle could prove to be less error-prone than human. Cars with advance safety features and eventually self-driving capability is a key aspect of the industry's effort toward safer roadways.

The impact of self-driving technology can be far-reaching, including less demand on emergency response systems and less auto insurance and health care costs. If ten percent of all cars are self-driving, as many as 211,000 accidents could be prevented annually [3]. About 1,100 lives could be saved. The economic costs of automobile accidents could be reduced by more than $20 billion.

## II. Benefits of Self-Driving Cars

In addition to safety, there are many other benefits of self-driving cars [3]. First, human productivity can be improved. For the 86% of the US work force that commutes by car, on average 25 minutes are spent one way each day. Self-driving cars could change commute time to productive time. For example, people can work on a project, write an email, check kid's schoolwork, make phone calls or text messages, read book or listen to podcast, or simply enjoy the ride.

Second, traffic congestion will be reduced. One of the leading causes of traffic jams is selfish behavior among drivers. If drivers space out and allow each other to move freely between lanes on the highway, traffic would flow more smoothly. Self-driving cars can be programmed to space out automatically, and thus help reduce congestion. In addition, with traffic information, self-driving cars can calculate alternative and more efficient routes in real time.

Third, drivers spend less time on parking. Self-driving cars can be programmed to drop “drivers” off at the front door of the destination, park themselves, and come back to pick them up as being called or scheduled. Furthermore, it does not matter that much how far away a parking space is because people are not going to walk from and to the vehicle. The autonomous car can behave like a taxi.

Fourth, the mobility for children, elderly, and disabled will be improved. Parents would not need to worry about driving kids to school in the morning, picking them up in the afternoon, or sending them to different activities. The lives of the elderly and disabled people can be changed dramatically as well, because the car can be programmed to pick them up and send them to their destinations. They will be provided with critical mobility.

Fifth, cars can be lighter and more versatile. A lot of weight in today’s cars is because of safety equipment, such as crumple zones and steel door beams. Self-driving cars are less likely to crash, and thus the need to build cars to withstand terrible crashes will be reduced. Cars can be lighter and more fuel-efficient. There could be more interior room because control mechanisms such as steering wheels can be eliminated. The interior layout design will be more versatile.

## III. History of Self-Driving Technology

People have been dreaming about self-driving cars for nearly a century [4]. The first vehicle that anyone really considered "autonomous" was the Stanford Cart, a precursor to the moon rover [5]. First built in 1961, it could navigate around obstacles using cameras and an early version of artificial intelligence. One problem of Stanford Cart is that it needed about twenty minutes to plan every one-meter move.

Figure 1. Stanford Cart

In 1995, Carnegie Mellon University researchers Todd Jochem and Dean Pomerleau drove across the country in NavLab 5, a 1990 Pontiac Trans Sport equipped to drive itself [6] [7]. For nearly 3,000 miles, using a windshield-mounted camera to detect lane lines, the van steered itself, while the humans handled the gas and brakes.

Figure 2. Carnegie Mellon NavLab 5

In the early 2000s, the Defense Advanced Research Projects Agency (DARPA) decided to speed up self-driving development with an open-to-all-comers race across the Mojave Desert. None of the fifteen vehicles entered the event completed the race, but the race created a new community of people who were interested in solving the challenge. The best performer was Carnegie Mellon’s Sandstorm, a Humvee that equipped with cameras, laser scanners, radars, and a 1,000-pound box full of electronics to make its way through the difficult terrain.


Figure 3. Carnegie Mellon Sandstorm

DARPA repeated the Grand Challenge in 2005 [8]. This time five out of twenty-three vehicles completed the course. First among them was Stanford's Stanley, a Volkswagen Touareg. Stanley used a combo of cameras, radars, and laser scanners, and relied heavily on machine learning to understand the environment and how to navigate. These equipment and methods have become standard in the industry by now.

Figure 4. 2005 DARPA Grand Challenge

The third and final DARPA contest was the 2007 Urban Challenge, which was held on an abandoned Air Force base [9]. In this event, six teams finished, demonstrating that fully autonomous urban driving was possible. Carnegie Mellon, working with General Motors, took the first place with Boss, built on a Chevy Tahoe. The sensor-laden Boss was aggressive, pushing but not breaking the rules of traffic. Like all the top performers, Boss used a new lidar laser-scanning system made by Velodyne, which offered a detailed and 360-degree view of the environment.

Since the DARPA challenges, many events and autonomous vehicle system tests have taken place, for example, the Intelligent Vehicle Future Challenges from 2009 to 2013 [10], Hyundai Autonomous Challenge in 2010 [11], the VisLab Intercontinental Autonomous Challenge in 2010 [12], the Public Road Urban Driverless- Car Test in 2013 [13], and the autonomous driving on the Bertha-Benz historic route [14]. At the same time, research has continued at an accelerated speed in both academia and industry. The Google self-driving car [15] and Tesla's Autopilot system [16] are two examples of commercial efforts that receive most attention from media and public.

The extent to which a car is automated may vary from fully human operated to fully autonomous. The SAE J3016 standard [17] introduces a scale of 0 to 5 to define the level of vehicle automation (Figure 5).

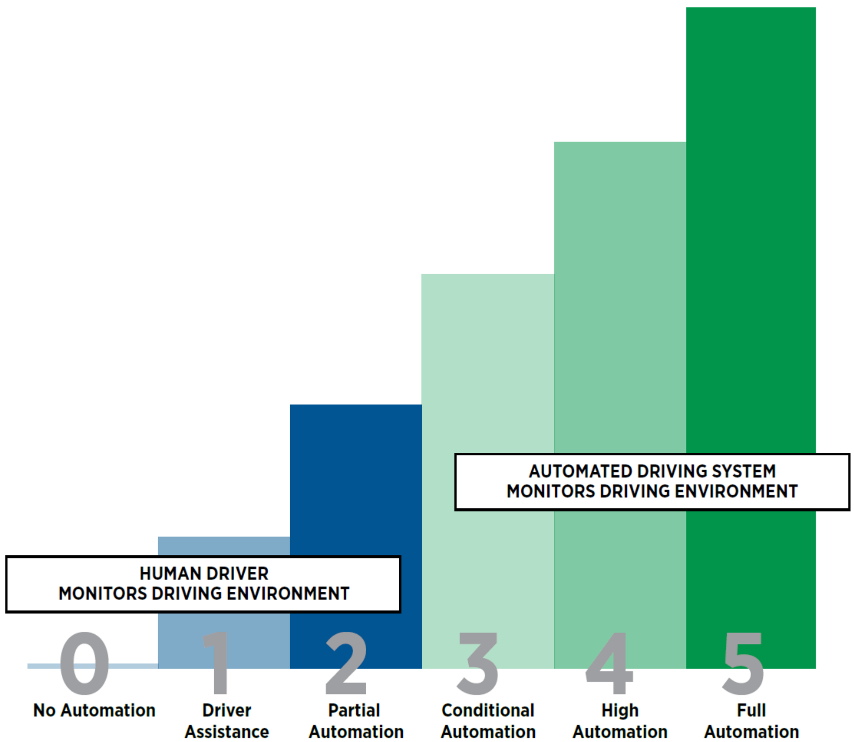


Figure 5. Taxonomy of Automated Driving Systems, SAE J3016 standard

In this standard, the level 0 means no automation. All driving tasks are the responsibility of a human driver.

Level 1 includes basic driving assistance such as adaptive cruise control, anti-lock braking systems, and electronic stability control [18].

Level 2 is partial automation. The “driving mode” specific execution is done by one or more driver assistance systems of steering and acceleration/ deceleration. The execution uses information about the driving environment and expects that the human driver performs all remaining aspects of the dynamic driving task. Such a vehicle is often equipped with advanced assistance such as hazard-minimizing longitudinal/lateral control [19] or emergency braking [20] [21].

At level 3, conditional automation, the system monitors the environment and can drive with full autonomy under certain conditions, but the human operator is still required to take control if the driving task is not in the autonomous system’s operational zone.

A vehicle with level 4 automation is capable of fully autonomous driving in certain conditions and will safely control the vehicle if the operator fails to take control upon request to intervene.

Level 5 systems are fully autonomous in all driving situations.

According to the estimates of automakers and technology companies, level 4 self-driving cars could be available for sale in the next several years.

## IV. Comparison of Tesla and Google Autonomous Car Technologies

In the race towards self-driving cars, Tesla and Waymo (from Google) are two of the most advanced companies [22]. There has been lots of speculation on how the two competitors make decisions on technology (control free vs autopilot), timelines, and potential market.

Currently, it seems Tesla gains an upper hand. The company has successfully launched semi-autonomous vehicles (Model S and Model X) to Indian market, while Google's Self-Driving Car (SDC) has been in development since the last decade (Figure 6). Google and Tesla differ from each other in the approach they take towards building self-driving cars. Their differences are mainly in two areas, computer vision technology and human car control.

Google embraced the LIDAR (Light Detection and Ranging) technology [23]**,** now a de facto standard for autonomous vehicles to form a 3D model of the world around the car (Figure 7). LIDAR is used to determine the size and distance of all things around the car in any circumstance or situation. However, LIDAR has its own challenges:

- LIDAR is expensive and proves complicated with moving parts.
- The 3D model of the world appears in low-resolution.
- It has relatively modest ranges of up to 100 meters.

Figure 6. Google Self-Driving Car (SDC)

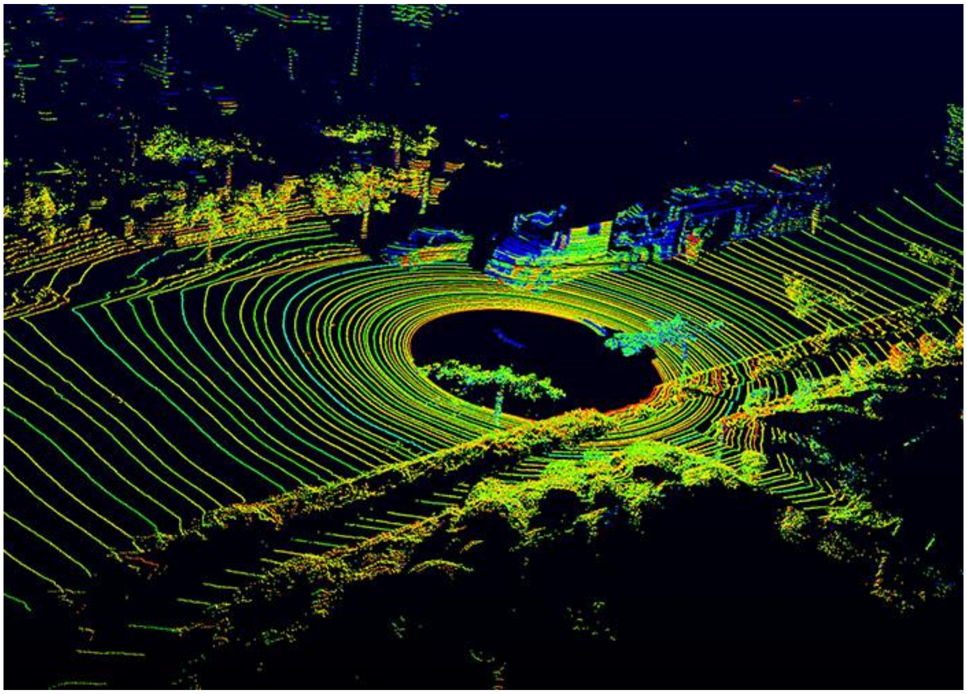

Figure 7. How Velodyne LIDAR sees the world [24]

Tesla uses an array of cameras for computer vision, unlike Google's LIDAR-based approach. Tesla CEO Elon Musk believes that camera vision will prove superior in the upcoming years. Camera vision eliminates or resolves the problems associated with the LIDAR-based approach. The camera approach uses digital cameras to interpolate a 3D world around the car. Camera vision technology can automate about 90% of driving (Figure 8 and Figure 9).

However, the camera approach has its own limitations. The cameras take and process data in a 2D, or stereoscopic (pseudo 3D) representation of the world. This is different from the real 3D data points received from LIDAR. The computer processing required to construct and understand the 3D world from the 2D data is very complicated and financially expensive as well.

Figure 8. Tesla Autopilot

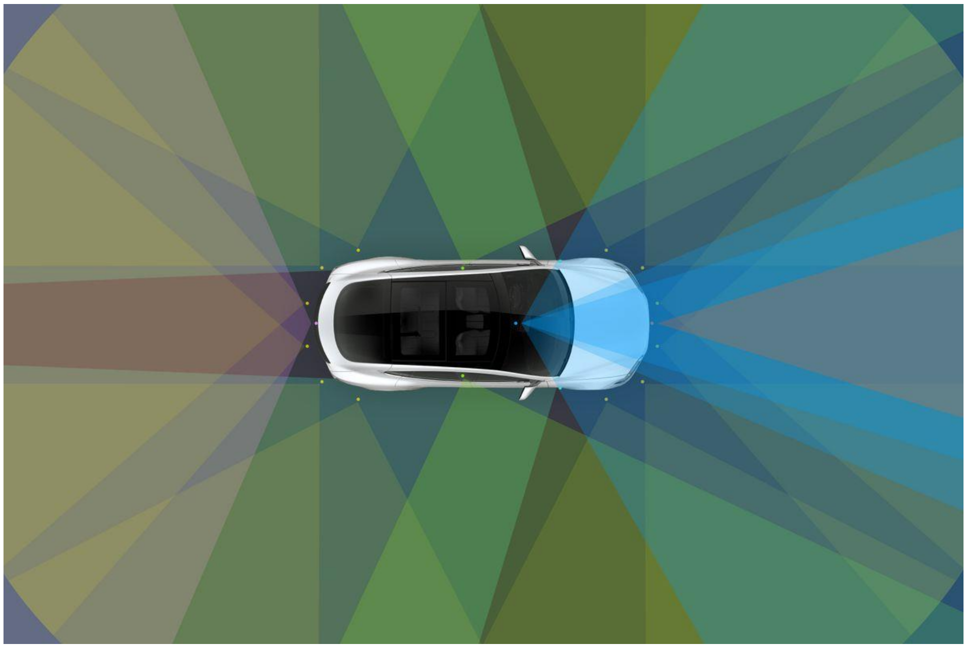

Figure 9. Tesla 8 cameras and 12 ultrasonic sensors [25]

The development of autonomous vehicles can have two different end points. They can be fully autonomous cars without the need of a driver, or they can be driver-managed autopilot-enabled cars. Google SDC exemplifies driverless cars, while Tesla model S is a good example of the second type. Driverless cars disallow any direct human control, while driver-managed cars use an autopilot paradigm that is inspired aviation.

## V. Technologies Needed for Self-Driving Cars

Self-driving is a very challenging goal and requires a wide range of technologies. The core tasks include learning the environment, tracking objects, localization, path planning, control, and system integration [26].

Learning the environment around the vehicle typically uses computer vision, deep learning, and sensor fusion. Computer vision deals with problems such as using a combination of cameras and software to find lane lines on difficult roads and to track vehicles (Figure 10). Deep learning has become the most important frontier in both machine learning and autonomous vehicle development. Deep neural networks need to be built and trained with data from the real world. Then the convolutional neural networks can classify traffic signs and can drive a vehicle in various environments.


Figure 10. Finding lane lines [27]

Tracking objects over time is a major challenge for understanding the environment surrounding a vehicle. Sensor fusion is a technology for this purpose. A fundamental mathematical tool called Kalman filters [28] can be used to predict and determine with certainty the location of other vehicles on the road. The following example shows that Kalman Filter works very well with

Lidar measurements [27] (Figure 11). Red circles are positions that Lidar reads, and green triangles are positions that Kalman Filter predicts.

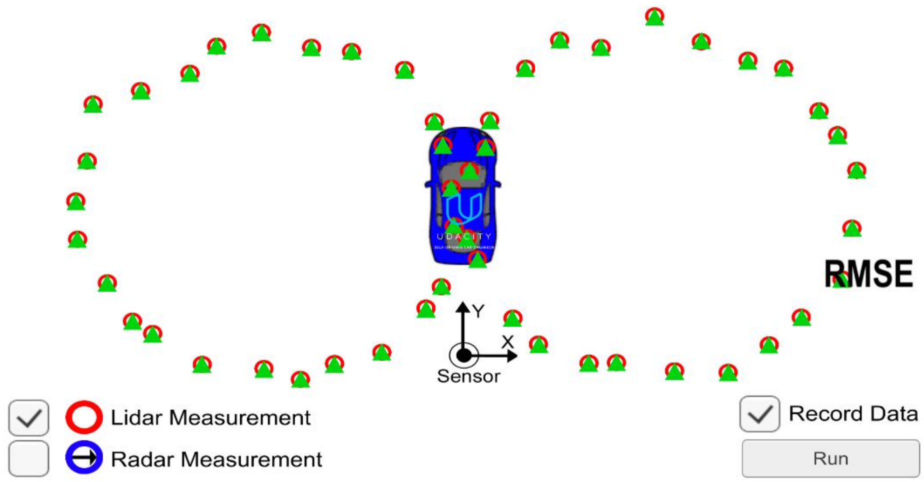


Figure 11. Kalman Filter with Lidar Measurement

Localization is how we determine where a vehicle is in the world. GPS is designed for localization purpose, but it is only accurate to within a few meters. Single digit centimeter-level accuracy is needed for self-driving. To solve this problem, the principles of Markov localization [29] can be applied to program a particle filter, which uses data and a map to determine the precise location of a vehicle.

Path planning routes a vehicle from one point to another. It also handles how to react when emergencies arise. This issue can be addressed through a three-stage path planning approach. First, model-driven and data-driven approaches can be applied to predict how other vehicles on the road will behave. Then a finite state machine can be constructed to decide which of several maneuvers the vehicle should undertake. Finally, a safe and comfortable trajectory is generated to execute that maneuver.

A self-driving car is still a vehicle. We need to control the car by sending steering, throttle, and brake commands to move the car through the environment. To actuate a vehicle, control algorithms such as proportional-integral-derivative (PID) controllers [30] and model predictive controllers can be used. Finally, system integration combines all components and functions and makes them work together as an integrated and harmonious system.

## VI. Conclusion

Autonomous driving is an exciting technology and is maturing at an accelerated speed. The race to first deploy self-driving cars is happening among carmakers, tech giants, and emerging startups. It’s possible that self-driving technology will significantly lower the number of yearly deaths from car crashes. There are also great financial incentives – Intel believes autonomous vehicles could generate $800 billion per year in revenue in 2030 and $7 trillion per year by 2050 [31]. Many technologies are needed for self-driving, such as cutting-edge of robotics, machine learning, software engineering, and mechanical engineering. These technologies bring a lot of learning opportunities for technology students. If prepared with necessary skills, they can launch a successful career as an autonomous vehicle engineer.

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