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Autonomous cars: Recent developments, challenges, and possible solutions

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Abstract. The development of production automobiles involved vehicles that were propelled by internal combustion engines. Improvements in the internal combustion technology continue to take place even today. However, electric vehicles are slowly making way into the bigger picture. Development in autonomous vehicle technology is also gathering pace. Although there has been remarkable progress in this domain, much needs to be accomplished. Adoption of autonomous vehicle technology has multiple benefits. Autonomous car companies have spent large amount of resources on the development of autonomous vehicle technology, with an aim to fully commercialize the technology. Several issues cause hindrance to the achievement of this goal. These issues comprise technical, non-technical and legal challenges. The future of the technology is assuring and ambitious, however, the challenges must be overcome.

1. Introduction

The history of the automobile dates to the year 1885 when the first production automobile was developed by Karl Benz in Mannheim, Germany. It was called “Benz Patent-Motorwagen” and used a gasoline-powered internal combustion engine. Then came the “Ford Model T” by Ford Motor Company in 1908, which was mass-produced on an assembly line. It was assembled at Ford’s Piquette Avenue Assembly Plant in Detroit, Michigan. During its production that spanned from 1908 to 1927, over 15 million Model T automobiles were produced.

There has been a lot of enthusiasm about autonomous cars. For an autonomous car to navigate effectively, technologies from multiple disciplines need to be combined. These disciplines broadly include computer science, electrical engineering, and mechanical engineering [1]. “Linriccan Wonder” of the 1920s was the first radio-controlled car. In 1939, electric cars powered by embedded-circuits were showcased. 1980 saw the advent of a robotic van by Mercedes-Benz, that used vision guided systems. This was the starting point for the origin of technologies used at present in modern vehicles. These technologies include lane keep assist, lane departure warning, adaptive cruise control, etc.

According to World Health Organization’s report on road traffic injuries (February 2020), there are approximately 1.35 million deaths per year, caused by road crashes. Most of these crashes can be attributed to human error. These errors can be caused by over-speeding, driving under the influence of alcohol or distractions during driving (such as usage of mobile phones). Other errors include non-usage of seatbelts, helmets, or other safety equipment [2].

These statistics advocate the need of broad adoption and advancement of autonomous vehicle technology. Without this, the number of transportation injuries and deaths are only expected to increase. The adoption of autonomous technology has multiple benefits, such as drastic reduction in the number of collisions, higher reliability, better flow of traffic and reduction in traffic congestion. According to a report by RAC foundation, “the average car is parked at home for 80% of the time, parked elsewhere for 16% of the time and is only on the road for 4% of the time”. This implies that on an average a car spends approximately 96% of the time in parking [3]. Thus, the advent of autonomous cars would reduce the need of private car ownership altogether, since a ride-sharing model that uses autonomous robo-taxis can be implemented. This potential use of a ride-sharing app will be implemented by Cruise in its “Origin” autonomous vehicle, which will not be available for private ownership at all. Autonomous vehicles can also be beneficial in the domain of delivery of goods, which can be made more reliable and efficient by their use.

Although autonomous cars provide a host of benefits, some challenges do exist in their development and commercialization. One of the primary challenges is the requirement of a legal framework and regulations. There may arise certain situations on road in which an autonomous system is unable to decide whether to save its own passengers, or other pedestrians/vehicle. Making a quick and rational decision under such situations is a challenging task. In addition to this, challenges about who is to be held liable in event of damage also remain. These challenges also induce fears in the minds of potential buyers. Thus, a clear and concise policy that addresses the concerns of a consumer is required. Also, challenges such as vulnerability to cyber-attacks exist. Some challenges have been discussed in the Challenges section.

1.1. Scope of the study:

This paper aims to discuss the recent developments and challenges in autonomous cars. It provides brief information about the history of the automobile in general, along with a brief history of autonomous vehicles. It also lays down the benefits of adoption of autonomous vehicle technology. The basic sensor-suite and key technologies used in autonomous cars have been discussed, along with the classification of vehicle automation. The recent developments in the industry with reference to three leading manufacturers *Waymo*, *Cruise* and *Argo AI* have been discussed in detail. The final section of the paper covers the challenges in the development and implementation and their possible solutions, with an in-depth detail on the technical challenges.

2. About autonomous cars

An autonomous vehicle can operate without requirement of any human control and can sense the environment. An autonomous car is sometimes called self – driving car, or driverless car.

It uses a combination of sensors, actuators, machine learning systems, complex and powerful algorithms to execute software and travel between destinations without a human operator. “The sensors gather real – time data of the surrounding environment including geographical coordinates, speed and direction of the car, its acceleration and the obstacles which the vehicle can encounter” [4].

Car navigation is achieved by Car navigation system, which is equipped with global positioning system (GPS) and geographic information system in order to gather information about location, such as latitude and longitude.

The location system uses inertial navigation system (INS) [5] to determine the relative vehicle location.

Electronic map (EM) stores information about traffic and road facilities, etc. HD map is an electronic map which is currently available for self – driving cars, and can be applied to level-2 / level-3 self-driving [6].

Path planning is primarily achieved by map matching, which calculates the location of the car.

For environment perception, three major methods are used: laser perception, visual perception, and radar perception.

In laser perception, concept of reflection time and reflection signal strength is used to generate cloud data of target point, such as location, state, and shape.

Light Detection and Ranging (LIDAR) is used for avoidance of collisions and in situations that require emergency braking. LIDAR systems emit multiple laser pulses per second. These pulses are reflected after interacting with surrounding objects. This helps create a 3-dimensional representation by calculations based on the speed of light and the distance covered by the pulse.

Radar perception is used for measuring distance by calculating the time taken by the wave transmitted by the radar sensor to return.

Short range vehicle to vehicle communication is used by self-driving cars, so that they can communicate with the surroundings and other vehicles. For this communication to take place, architectures must be redundant and real time [7].

Advanced Infotainment and uncompressed ADAS (Advanced Driver Assistance Systems) Sensor Data (Level 3 – 4 autonomy, refer below section) requires around 12 to 24 Gbps of network bandwidth [7].

"Vehicular ad-hoc networks (VANETs) are created by applying the principles of mobile ad hoc networks (MANETs) – the spontaneous creation of a wireless network of mobile devices – to the domain of vehicles" [8]. Connected cars use VANETs to communicate with each other. "In order to ease the integration of autonomous car with existing connected car technology, the autonomous car must use the same communication standard which is used for the connected car technology today." [9].

3. Classification of Vehicle Automation

The levels are based on the level of involvement of human in the driving process. According to the "National Highway Traffic Safety Administration (NHTSA)" [10], there are 6 levels of driver assistance technologies:

"Level 0: No automation" – All tasks are performed by the driver.

"Level 1: Driver Assistance" – Stand-alone vehicle components such as Electronic Stability Program (E.S.P) or Automatic Braking are present.

"Level 2: Partial Automation" – combined automated features such as steering / acceleration, i.e., lane-keeping and adaptive cruise control are present. However, the driver must always be involved in the driving and he/she must monitor the environment.

"Level 3: Conditional Automation"- The driver can fully cease control of some of the important function of the vehicle in certain conditions, but he / she must remain ready to take control of the vehicle at all times with advance notice.

"Level 4: High Automation" –The vehicle can execute all the driving functions. The option to control the vehicle may or may not be there with the driver.

"Level 5: Full Automation" – The vehicle is able to perform all functions related to driving, under all situations and conditions.

The levels have been demonstrated graphically in figure 1.

4. Recent developments in the industry

Recent developments in the applications and services provided by the VANET (Vehicular Ad hoc NETwork) technology [11], [12] include notifications about crash, prior warnings about accidents, construction on the roads, over-speed, traffic signals, warnings about fog, existence of black-ice, certain services based on location, etc. These developments, along with the developments in connected car technology [11], [12] have led companies such as Google, and car makers such as Tesla and Audi, to develop autonomous car technology. In addition to these manufacturers, the steps taken by leading car-manufacturers such as Ford, BMW, Kia, Hyundai, Honda, Toyota, Mercedes – Benz, General Motors, Volvo, Nissan and Volkswagen include emergency braking, smart parking, accident warning and semi – automatic pilot driving [9]. Today, partnerships between car manufacturers and technology companies have enabled them to design and develop driverless cars. For instance, Microsoft has partnered with Toyota and Volvo for the development of autonomous cars. In addition to Microsoft, Apple and Uber have partnered for the autonomous car project. In Europe, manufacturers such as

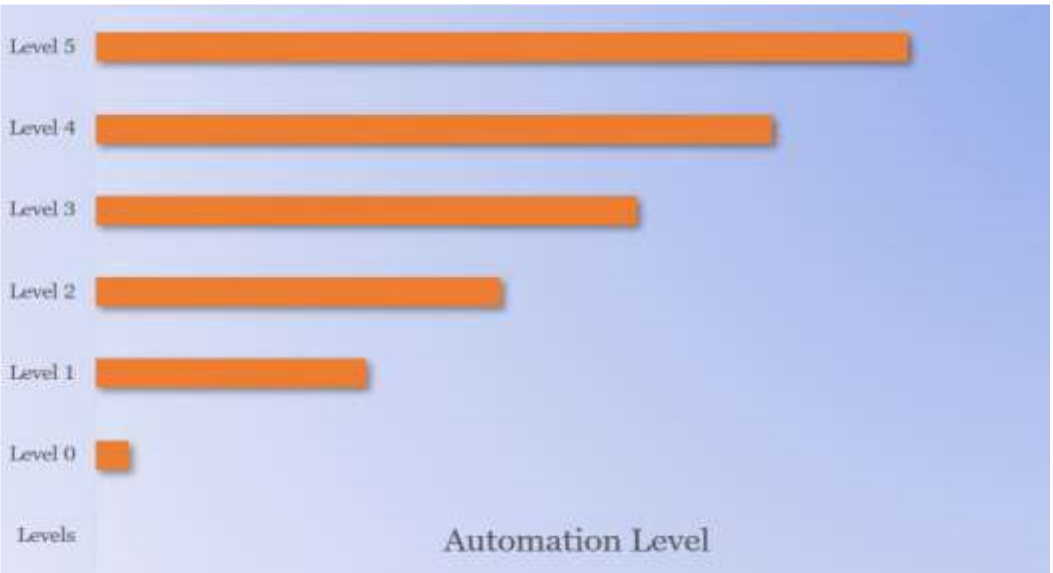

Figure 1. Graphical demonstration of automation levels.

Mercedes–Benz and BMW are leading the development of the concept of driverless prototype cars.

4.1. Waymo

Waymo is a driverless car technology company founded in 2009. It is a subsidiary of Alphabet Inc. Currently, Waymo is considered the leader in the development of driverless cars, as its autonomous cars have driven 20 million miles on the road and are closest to Level 5 of autonomy. According to Waymo Safety Report (2018), "Waymo's fully developed self-driving system is designed to operate without a human driver, unlike technologies sold in cars today such as adaptive cruise-control or lane-keeping systems which require constant monitoring by the driver" [13]. Waymo's primary test locations include Mountain View, San Francisco and Palo Alto in California, Phoenix in Arizona, and Detroit in Michigan.

Waymo's technology of autonomous cars comes under Level 4 automated driving system of SAE International, as the technology can also completely stop the vehicle in the event of any system failures. Figure 2 shows the sensor systems on Waymo's new Jaguar I – Pace vehicle. The sensors used allow the vehicle to see 360 degrees, both in daytime and at night. The set of multiple sensors assists in generating a 3-dimensional picture of the surroundings and shows static and dynamic objects. These objects include vehicles, construction equipment such as warning cones, traffic lights, and pedestrians. LIDAR system beams out millions of laser pulses per second, in 360 degrees, and measures the reflection return time. Waymo's mid-range and long range LIDAR have been combined into a single rooftop unit to provide a 360-degree view. The high-resolution vision system uses cameras that see the world in context – in 360 degrees field of view. The radar system makes use of wavelength to track objects and motion. It is effective in all lighting and weather conditions, such as snow, fog and rain [13]. In addition to the above-mentioned systems, Waymo vehicles also use sensors such as GPS, and a system that detects audio (sirens) from emergency service vehicles that are far away, in order of hundreds of feet. Perception, Behaviour Prediction, and Planner are the three major components of Waymo's software. In 2019, Waymo partnered with Jaguar Land Rover (JLR) for up to 20, 000 modified all - electric Jaguar I – Pace vehicles to be used as robo-taxis [14]. Each vehicle has 29 cameras, located in the front and back, sides and top of the vehicle.

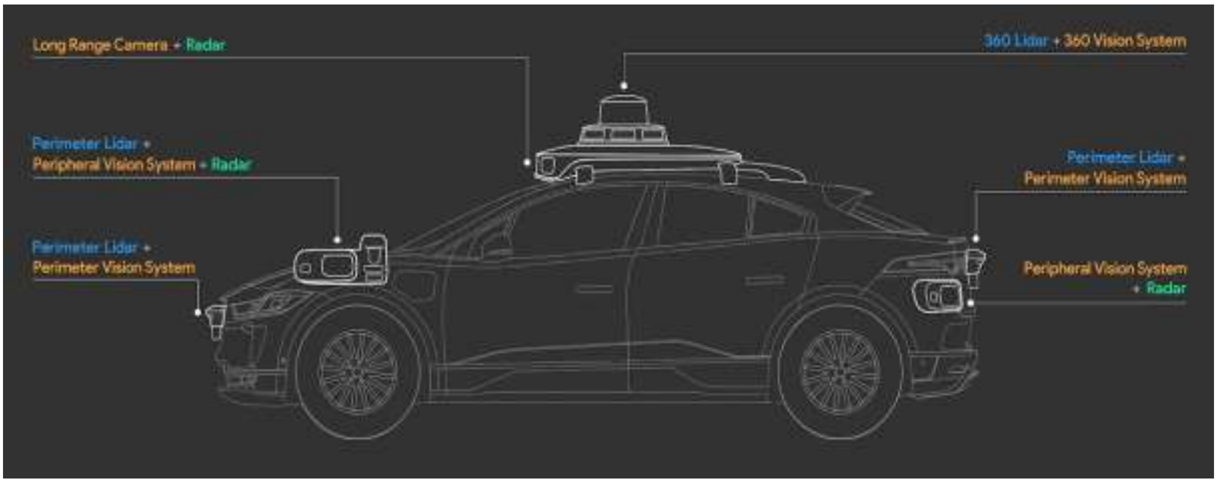

Figure 2. This schematic shows the sensor systems on the vehicle. *(Image courtesy Waymo)*

4.2. Cruise
Cruise is an American autonomous car company. It was founded in 2013. In 2016, it was acquired by General Motors. Since then, the company is developing software for General Motors Chevrolet Bolt. This software would be used to make the car autonomous. The Bolt uses several LIDAR sensors from Velodyne. In January 2020, Cruise unveiled the Origin, which is a fully autonomous car without a steering wheel or pedals. This enables the EV to go straight to level 5 (or level 4 within defined areas) of autonomous driving. The vehicle has a symmetrical design, with the 2 rows of seats facing each other. It is designed to do highway speeds. The vehicle is modular and will have a lifespan of 1 million miles – six times more than the average car. Individuals will not be able to purchase the Origin as a personal vehicle. Rather, it would be used as a taxi under Cruise's own ride sharing service. The digital overhead displays give traveller and route-information. The vehicle is fitted with 'owl', which is a hybrid sensor assembly that combines both camera and radar [15].

4.3. Argo AI
Argo AI is a company that is developing a fully integrated self-driving system. This system is intended to be used for ride-sharing and delivery of goods. For this purpose, Argo AI is working with leading automakers such as Ford and Volkswagen. Currently, the company is developing technology strictly according to Level-4 of automation. The company's focus is on developing a complete product that comprises the software platform and all the sensors, including LIDAR, light detection, radar and cameras. The company also uses an Autonomous Vehicle Platform. This platform is a set of traditional tools that has been adapted in order to control the vehicle with commands that are generated by the computer [16].

In order to solve two major technical challenges – perception and decision-making, Argo is following the approach of using machine learning algorithms to surround the problems that are solved by using deep networks. The company uses Ford Fusion Hybrid cars for the testing purposes. In some urban areas, Argo AI is developing and testing goods delivery vehicles. In June 2019, Argo AI and Carnegie Mellon University announced a five-year, $15 million research partnership in which the company will fund the research into advanced algorithms for autonomous vehicles. It is called "Carnegie Mellon University Argo AI Center for Autonomous Vehicle Research" [17].

Argo AI has developed redundant systems for braking, steering and power, so that alternate systems can take control in event of a power loss. This is done keeping in mind the possibility of failure of the 12-volt power system of a vehicle, in which case a driver of a traditional vehicle would be able to stop the vehicle by pressing the brake pedal [16]. The backup electrical power sources are available for several components, so that in case of failure, these components, which include computers, sensors, braking and steering systems), still get low voltage power to stop the vehicle [16].

5. Challenges and Possible Solutions

This section includes the various challenges that must be addressed in order to ensure smooth development and proper commercialization of autonomous cars. The technical challenges are discussed below in detail:

5.1. Safety and Reliability

Before full commercialization, the technology must be tested for several million miles. The reliability of a system is determined by the distance travelled by the car. As per the requirements, an autonomous car must drive around 291 million miles without loss of lives (by accidents) to ensure a 95% equivalence to a human driver [18]. These requirements for miles and the resulting number of years remain too high, even if we reduce the percentage of equivalence required. Another factor for comprehensive safety test is the number of "challenging / difficult" miles. According to the 2018 safety report by General Motors, the number of challenging on-road situations, such as construction-blocked lanes and left turns, are 40 times higher in San Francisco, CA than in Phoenix, AZ. Even though the vehicles tested in "easy miles" locations will accumulate miles at a faster rate, but the amount of learning would be less substantial.

Even though the California state law has allowed the testing of fully autonomous cars without safety drivers on public roads (since February 2018), the deployment remains a challenge due to lack of trust. The first fatal crash occurred in March 2018 when a Level-4 Uber prototype crashed into a pedestrian crossing a road [19]. According to the NTSB report, there were two points to note: First, the automated emergency braking system was disabled on the test vehicle, and second, the pedestrian was detected, but was not identified correctly as a human. This incident, along with another fatal incident that occurred 5 days later involving a Level-2 Tesla Autopilot system, raised questions about the safety and maturity of autonomous cars [19].

Considering these prospects, the University of Michigan's autonomous car testing facility 'Mcity' at Ann Arbor, Michigan has proposed an independent safety test, called the Mcity ABC Test. The main aim of the Mcity ABC Test is to test the performance of automated vehicles, in terms of safety. It consists of three main components: Accelerated evaluation, Behaviour competence, and Corner cases [19].

Accelerated evaluation focuses on three main scenarios: lane change, car following, and left turns. In Accelerated evaluation, initially naturalistic driving data is collected. This data reflects what the test vehicles will be facing in normal conditions on public roads. In the next step, driver behaviour is 'skewed', i.e., risky behaviour is boosted and focus on 'challenging / difficult' miles is increased.

Behaviour competence involves testing the vehicles in rigorous scenarios to see how they perform in terms of safety. Waymo list [13] is also one of the collections of scenarios. A total of 50 scenarios are selected. Weather and lighting are also one of the factors that are considered. Lighting conditions are tested under daytime and night-time. Components such as radars, LIDARs, and cameras are tested in rain and snow. After this testing, 35 scenarios have been finally selected. Further testing shows that for low-speed shuttles having GPS-defined paths, only 16 scenarios are needed.

Corner cases involve cases that are on extremities of the test conditions. For instance, one of the corner cases can be detecting dark coloured cars in dark surroundings using cameras. Zig-zag motion of joggers on the street, cyclists taking left turn in busy traffic are some of the challenging cases enlisted in the Waymo Safety Report.

5.2. Validation and testing:

Autonomous systems require comprehensive testing, because the system is complex, and any decision made by the software affects human lives directly. The ISO 26262 standard provides a framework for vehicle-guidance systems considering the functional safety [20]. The V – model has been used for a long time in the automotive industry and is the universal ISO 26262 standard. This model works fine for generic automotive systems. However, due to a complex set of requirements and a high degree of uncertainty in autonomous systems, the traditional validation and testing techniques are not feasible. Thus, an alternative approach is needed. Machine learning has a probability of being more powerful for building an exhaustive system that helps in decision-making. Machine learning involves many types such as supervised learning, unsupervised learning, deep learning, semi-supervised learning, active and inductive learning. For the purpose of detection of objects, the classifiers of machine learning algorithms need to be trained on large amount of data [9]. This makes the testing process even more challenging.

Fail-operational system design is also a challenge, because at least two independent, redundant subsystems are required, so that if one part fails another one can take over [21].

Fault injection techniques use external equipment to introduce defects into the hardware of a target system. These defects may be introduced with or without contact. Faults such as forced voltage changes, forced current addition can be introduced by direct contact. Fault injections such as exposure to magnetic field can trigger bit flips and hardware faults. These faults are introduced without making physical contact [22].

5.3. Orientation (knowledge of position relative to surroundings)
Multiple factors contribute to the orientation challenges faced by autonomous vehicles. The primary cause of this problem are the dynamic situations on the roads, such as road diversions, construction sites, and missing road signs and markings. Multiple strategies have been adopted by different companies to overcome this challenge [23]

Real time image processing and machine learning approach, that has been deployed in Tesla vehicles has multiple benefits. It enables the vehicle to adapt to the dynamic environmental conditions. Although complex, this approach eliminated the dependency of the vehicle on outdated maps.

Companies such as General Motors and Mercedes Benz rely on LIDAR to implement a pre-recorded 3-dimensional map of the surroundings. The vehicle detects changes in the environment using the pre-recorded map and LIDAR equipment, and responds to the changes accordingly. Although the costs of LIDAR equipment and recording maps are high, this method is highly reliable.

Another approach to overcome the challenge orientation involves creation of smarter environments. The environment informs the vehicle about change in surroundings. “Vehicle-to-everything (V2X) suite” is also a component of this approach. It is used by Volkswagen in its vehicles. Volkswagen has also incorporated “Vehicle-to-Infrastructure (V2I)” testing with smart traffic lights. This approach of creating smarter environments reduces the complexity of autonomous vehicle systems.

5.4. Legal challenges
The requirement of a legal framework and regulations is one of the most important requirements for deployment of autonomous vehicles. The question of who is to be held liable in event of an emergency/collision is also another challenge. With the development of autonomous vehicles, there is a clear shift of responsibility for accidents from drivers to the companies that design and develop these vehicles. Therefore, it is imperative that laws are revised, considering the presence of autonomous vehicles on public roads. A clear and concise policy that addresses the concerns of a potential consumer is required.

5.5. Moral and ethical aspects
Another major challenge involves decision-making in the event of emergency situations. When confronted with challenging situations on the road, autonomous cars may face decisions having moral implications, such as necessarily deciding between putting the lives of the passengers at risk versus crashing into a nearby pedestrian, or slamming the brakes to avoid hitting the pedestrian which may put the lives of the passengers at risk. Making justifiable decisions under these situations could be a daunting task.

As of February 2020, the only country in the world with actual guidelines on the decision making of autonomous vehicles is Germany. According to a 2017 report on ‘Autonomous and Connected Driving’ by the German Ethics Commission [24], “In the event of unavoidable accident situations, any distinction based on personal features (age, gender, physical or mental constitution) is strictly prohibited. It is also prohibited to offset victims against one another. General programming to reduce the number of personal injuries may be justifiable.” Although this may seem ideal, these preferences may vary due to differences in moral attitudes. For example, according to “The Moral Machine Experiment” [25], people tend to give preference to saving the young over the old, saving more lives in preference over fewer lives.

To overcome these challenges, all the stakeholders must be transparent about the choices and the rationales backing them, while analysing the risks and benefits associated.

5.6. Financial challenges
High cost related to development and adoption of autonomous vehicles is a challenge. The technology and components, such as sensors and communication devices used in vehicles with higher levels of automation could result in these features being available in only premium tier production vehicles, raising questions about affordability for end-consumers.

One of the possible solutions for higher costs could be the use of hiring (ride-sharing) model for vehicles, operated by for-profit organizations. Robo-taxis, such as those planned by Cruise for its ‘Origin’ vehicle, are based on this model. This model would result in distribution of costs over a large number of individuals. By analyzing the costs associated with robo-taxis implementing the ride-sharing model, the primary contributor of high fares would be the utilization rate of the robo-taxis, which is the time spent by the vehicles in transporting passengers. This rate currently stands at 50% for current taxis. [26]

Therefore, in order to ensure significant adoption of autonomous vehicles in future, the technology must be affordable.

6. Conclusion
Although autonomous car companies have made phenomenal progress in the technology, it will still take many years for fully autonomous cars to become available to public. Specifying a definite year may not be possible at this stage. According to some predictions, cars may become fully autonomous by 2035. Even though the technology is developing, we must also be ready to utilize it. Also, the challenges discussed earlier must be overcome in order to ensure a smooth development of the technology. It is hoped that this paper provides clear insight into the field of autonomous vehicle technology.

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