Coordination of Autonomous Vehicles

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***Abstract*–Some vehicles today can drive autonomously at an impressive level; the next step would be for them to start coordinating. To understand the current extent of knowledge on the coordination of autonomous vehicles (AVs), this paper briefly views the historical context of the AV, uses a system to identify and appraise the current state of the AVs, researches the communication methods to approach coordination as well as coordination problems and protentional solutions, inspects the key challenges and barriers to further developing the current knowledge and practice of coordinating autonomous vehicles, and discusses with consideration to the content already talked about, how research into this subject should proceed.**

***Index Terms*–Autonomous Vehicles (AVs), coordination, ethics, future predictions, problems.**

I. Introduction

ON the 29th of January 1886, the patent for what may be regarded as the invention of the automobile was applied for by Carl Benz [1]. The patent was for the design of a vehicle that was powered by a gas engine. Almost four decades later when vehicles had become the norm, the first remote-controlled driverless car was demonstrated at McCook air force test base. It was controlled by a person who was tailing it in a separate vehicle from 30 meters away [26]. Today the term driverless is less associated with a remote-control car but more with autonomous vehicles (AVs). In the current transportation climate, the number of AVs entering the roads around us is increasing at an unprecedented rate. Technological improvements in modern vehicles have slowly taken an increasing number of responsibilities away from the driver especially with the rise of self-driving capabilities. Examples of these AVs include the four models Tesla offers: Model S, Model 3, Model X, and Model Y [3]. All new Tesla cars come standard with advanced hardware capable of providing Autopilot features today, and full self-driving capabilities in the future. Some of these features include steering, accelerating, and braking automatically within its lane, as well as smart summon which allows the vehicle to navigate complex environments to find the driver in a parking lot [2]. Currently, AVs work independently to complete their goals such as switching lanes and following a path to their destination without the consideration of what other AVs want to achieve. Having AVs work together could be mutually beneficial as seen in experiments such as when a group of University of Cambridge students created their miniature car called the Cambridge Minicar and gave it the ability to drive autonomously. With a fleet of these cars coordinating, they discovered that traffic was sped up by 35 percent [9].

II. The History of Autonomous Vehicles

DUE to 200,000 US citizens being killed in car accidents each year in the 1920s, driver error was considered by many to be the greatest cause of this issue. This generated the idea of introducing technologies to the vehicle to reduce or eliminate human error. Around the same time, technological discoveries in radio engineering and aviation were made, the gyroscopic Airplane Stabilizer which we know today as the first autopilot was created, and the US military developed remote control of moving mechanics using radio waves which were used to experiment with remote-controlled torpedoes, ships, and aircraft [26].

On the 5th of August 1921, a breakthrough event happened at the McCook air force test base in Dayton, Ohio. The first remote-controlled driverless car was demonstrated, a person could control the car from 30 meters behind it via radio. Fast forward four years, in 1925 another remote-controlled vehicle called the American Wonder was introduced to people as it drove down Broadway in New York, which also was controlled from a second vehicle just like the previous one. In the early 1930s to late 1940s, these remote-controlled vehicles appeared in public for either commercial advertising or to take a role in Safety Parades [26].

Fig. 1. An early version of a radio-controlled car design and tested at McCook Field by the U.S Army Air Service in 1923. [6]

In 1935, General Motors present a short film called The Safest Place to educate viewers on road safety, this film was the first screen appearance mentioning self-driving cars. The film placed the blame of accidents on driver selfishness and uncooperativeness, suggesting that if the manufacturer could equip every car with an automatic driving mechanism, the car would always do just what it should do when it got out on the road. Even though the self-driving car was an abstract concept at the time, the idea of having it seemed more beneficial than relying on drivers. The first film with a fully functioning AV was The Love Bug (1968) [26].

During the mid-1930s, the solution to driverless cars shifted away from remote controls to a guiding system. In May 1938, Popular Science introduced a wire guidance system for automated driving to end accidents made by human drivers and bad roads. All vehicles would follow an electromagnetic wire embedded into the road which would regulate speed and steering. Decades later this became a reality as on the 14th of February 1958 at GM's Technical Center in Michigan, the first automatically guided vehicle, a 1958 Chevrolet with two electronic sensors attached it, followed a wire on the road as it steered accordingly on a one-mile route. In 1958, the vision of an automatic highway started to fade as Chrysler developed an "autopilot" device for vehicles which was a knob that allowed the driver to set the speed of the car. The confidence in the vision also decreased as that the idea was not economically feasible [26].

One of the biggest hurdles in creating fully AVs which are not reliant on the guide wires was giving vehicles the ability to see. In 1977, a team lead by Sadayuki Tsugawa in Japan created a vehicle that could record and process pictures of lateral guide rails and move with a speed of 10 km/h. This was around the same time the increasing use of microelectronics in vehicles was happening. In the 1980s, Ernst Dickmanns and his team developed a visually guided autonomous 5-ton van that was able to brake, steer and throttle through computer commands based on evaluation of real-time images. Dickman's success convinced the industry to persuade the concept of machine vision to detect objects rather than use electromagnetic fields generated by cables in the roads to guide cars. During the 1990s, the team of Dickmanns developed with Mercedes Benz two AVs which drove more than 1000km on three-lane highways with heavy traffic in France for speeds up to 130 km/h. They automatically completed tasks such as steering, lane changing, and braking. Other projects followed this success with some AVs driving longer distances [26].

III. The Current State of Autonomous Vehicles

When identifying and appraising the current state of self-driving cars, a system needs to be used which allows us to determine where AVs today stand between the range of fully manual to fully autonomous. A popular system I have chosen created by SAE classifies the autonomy of a vehicle into six levels, starting at level 0 where the vehicle has no driving automation to level 5 where the vehicle has full driving automation [14]. The level at which an AV resides is determined by four categories.

The first category considers whether sustained lateral and longitudinal vehicle motion is controlled by the driver, self-driving system, or a combination of both. The longitudinal controller regulates the velocity of the vehicle while the lateral controller regulates the steering of the vehicle to maintain its current path. The autopilot system in AVs in the present state can sustain lateral and longitudinal motion control without the need of a driver which places it in levels 2 and above [17].

The second category critics the autopilot object and event detection and response (OEDR), this is a sub-task of dynamic driving task (DDT). It refers to the immediate response of a system or driver to respond to a driving task upon detection of it. For example, Tesla's autopilot has a collision avoidance assistance system in place that activates to reduce the impact of an unavoidable frontal collision [16]. Currently, AVs are only capable of limited OEDR as there are some events it is not capable of recognizing or responding to, this section classifies it as level 2.

The third category is DDT fallback, this is whether the driver or auto pilot system is responsible for the operation of the vehicle to perform safely on the roads and in traffic. Currently, a person driving an AV is still responsible for its operations and safety, automatic features such as lane swapping, or collision prevention do reduce the tasks of the driver, but the self-driving system is yet to replace them. Tesla has even stated that current Autopilot features require active driver supervision and do not make the vehicle autonomous [2]. Due to drivers being required to constantly supervise the driving automation system, current self-driving cars would be placed in level 2 for this category. To make the jump to level 3, it would require the driver to only intervene with the automated driving system when requested.

The final category involves the operational design domain (ODD), it is the domain in which a self-driving car is designed to operate. A limited ODD means the automated system is constrained to certain domains such as roadways, speed ranges, and weather types. An unlimited ODD is when the self-driving car is not constrained and can operate in all environments and conditions. Currently, only a level 5 automated system can have an ODD of unlimited.

With consideration of all categories, AVs currently are at level 2. Although there is a considerably long way to go to achieve full driving automation, we are on the verge of level 3 AVs. Honda has planned to release their Honda Legend sedan 2021 with level 3 autonomous driving capabilities exclusively in Japan by the end of March 2021. The vehicle will operate without the driver needing to watch the environment unless it indicates that the driver needs to take control. This feature is only available in certain conditions such as when the car is in congested traffic on the expressway [8].

IV. Achieving Coordination

A. Communication

THE future of coordinating AVs relies on the advancements of connected and automated driving (CAD). CAD involves using technology for the vehicle to vehicle (V2V) communication, vehicle to infrastructure (V2I) communication, and retrieval of any useful external information out of reach of the vehicle's sensors such as GPS to allow an AV to travel as safely and efficiently as possible [7]. For AVs to coordinate with each other, they must be able to connect to an entity to retrieve or send information, this can be achieved by V2V or V2I.

A method for sharing information is by using pure V2V communication in a Vehicular Ad Hoc Network (VANET). This VANET would be a decentralized type of wireless network with no pre-existing access points, instead, vehicles act as nodes that forward data between each other. The nodes that do forward data depend on factors such as the routing protocols. A key requirement for the implementation of VANET applications is the availability of efficient and effective routing protocols to spread messages. The many VANET protocols that have been proposed can be classified into five main categories, namely broadcasting protocols, route-discovery protocols, position-based protocols, clustering-based protocols, and infrastructure-based protocols. A clustering-based protocol appeared to be the most promising one as it captures the mobility of VANET nodes naturally. A MOving-ZOne-based (MoZo) architecture with a clustering-based protocol was created to allow vehicles with similar movement patterns to be grouped into a zone. Each zone has a vehicle elected to be its caption; this vehicle is responsible for managing information about other member vehicles in addition to sharing messages to its members and other captains. Moving zones are constructed when a vehicle logs onto the VANET, it will execute a joining protocol to find nearby moving zones or create its own [10]. This would allow coordination to be achieved by only needing to communicate with certain nodes instead of sending information to every node.

To allow the MoZo architecture to work, an approach would be to implement a radio communication technology that allows for proximity messages to be sent and received called Bluetooth Low Energy (BLE). The vision considers the BLE-based information-sharing framework to be a beneficial alternative method to other V2V communication methods as it requires significantly lower energy consumption, has a low deployment cost due to the Bluetooth technology being widely used, and it does not need to connect to a communication network infrastructure [19]. As BLE is independent of a central network, information is only shared when needed, such as two captains exchanging their zone information as they drive towards each other.

An alternative to the V2V method is to make information shared by using V2I, this involves communication to a central system which would give AVs the medium to communicate with any other AV connected to it. This brings its own set of advantages and disadvantages when compared to V2V. Benefit-wise, vehicles will not need to be within a certain range of each other. On the other hand, there would be a large reliant on this communication system, a failure in the system could result in AVs being unable to coordinate at all. For vehicles to be able to send and receive large amounts of external information from a central system, powerful wireless technology is required, one possibility is the fifth generation of the wireless network (5G), this technology is expected to support V2I communication [25].

B. Degree of Autonomy

MANY approaches to coordination have been proposed through literature to address identified vehicle coordination problems. Four identified main classes of coordination approaches center around the concept of the degree of autonomy. This is the extent to which vehicles can control their actions while coordinating. These are centralized, negotiation, agreement, and emergent. Centralized is where a single entity known as a coordinator entirely oversees coordination. It decides on the outcome of all coordination by deciding on how all vehicles must act. Negotiation protocols allow coordinating vehicles to propose solutions to perform from a set of admissible moves. The protocol will eventually guarantee the convergence towards an equilibrium solution if design properly. This solution will dictate what actions vehicles will perform and when they will be performed to solve the coordination problem. Agreement is where coordinating vehicles participate in a dynamic protocol defined by themselves in a collective way in which the outcome is both a set of admissible moves and possibly even a dynamic re-determination of the goals to be achieved during the coordination process. Emergent is where coordinating vehicles do not explicitly engage in any coordination protocol, they instead act selfishly according to their goals and to maximize the utility of their actions [11].

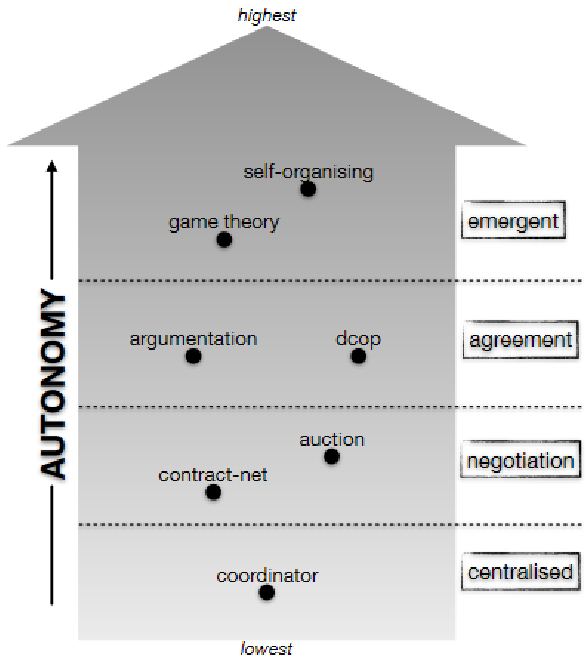

Fig. 2. Coordination approaches are categorized according to an increasing degree of autonomy in decision-making left to vehicles during the coordination process. [11]

C. *Coordination Problems and Solutions*

THERE have been many different solutions to coordination problems written in literature. These solutions change depending on the degree of autonomy. Some examples of these problems include platooning, smart parking, ride-sharing, and traffic flow optimization. Platooning is where a fleet of vehicles travel as if they were a single entity. In a centralized approach, a platoon leader is chosen and responsible for communicating with the other vehicles and providing the speed profile to which they must abide. This communication approach is like the MoZo architecture previously discussed [11].

Smart parking is a resource-oriented coordination problem, competitive for individual vehicles but collaborative for vehicles in a company fleet. In a centralized system, AVs would request parking from a certain central authority for a specific time and place, this authority would then assign them a slot according to its policy. A negotiation approach would involve AVs undertaking a two-stage negotiation with a broker agent. This agent will take into consideration the parking fees, distance to the parking spot and the destination, and its booking and reservation policies when deciding who gets which parking slot [11].

Ridesharing is an umbrella term for highly related sub-problems such as carpooling, this is more relatable to future autonomous taxis in my opinion. Current taxi services such as uber use a centralized approach to solve constrained optimization problems aimed at matching supply and demand while complying with time-based and route-based constraints. A negotiation approach to a request for transport from a pedestrian would be to have the autonomous taxis use negotiation techniques such as competing in an auction or Contract Net to determine which vehicle would be the pickup [11].

Traffic flow optimization involves directing traffic across a road network to minimize traffic jams and travel times. Today's attempts at influencing vehicles are through the approach of adapting traffic light schedules and digital signages. With AVs, the approach will be different. A centralized approach would have AVs receive guidance from a centralized traffic management system instructing them on which routes to avoid. While negotiation and agreement approaches can hardly apply to this problem, emergent approaches can guarantee the achievement of specific properties at the global, collective level, but the downfall of the approach makes it no longer possible to control the behavior of individual vehicles [11].

V. WHAT ARE THE KEY CHALLENGES?

ONE of the key challenges in adopting this technology is solving the issue of security, a solution for the privacy of data and the prevention of malicious attacks needs to be created before sharing data between AVs is implemented. Data sent between entities, either by V2V or V2I, needs to be secure and anonymous. Secure data is crucial because just as how AVs use global navigation satellite systems (GNSS) to accurately retrieve their position on a map, they would also rely on the accurate exchanging of information from other vehicles or retrieval of information from infrastructure to influence their decision. As the injection of fake messages and GNSS spoofing is claimed to be the most dangerous attacks for AVs, the same logic could apply to malicious messages sent via communication, therefore the protectiveness of cybersecurity is an issue that would affect the reliability of this system. In a potential scenario, manipulating data sent to the AVs could provoke erratic inaccurate maneuvers which could endanger passengers' lives [4]. With privacy, due to the system sharing real-time sensitive information about the vehicle, an attacker could intercept the messages to gather sensitive information about an AV.

When AVs have reached a point where they are safer and more efficient than a human driver, we can assume that human drivers will no longer exist. In the meanwhile, there will still be a transition period of all human-driven vehicles on the road becoming autonomous. This creates the challenge of having AVs coordinate with each other while there being human drivers around them. Some scenarios could involve human-driven cars in the process of coordination but only if there is the existence of means for AVs and human-driven cars to communicate with each other [11]. On the other hand, human drivers can be considered obstacles for different coordination methods. For example, AVs might not be able to platoon because human drivers might be between them.

Quality of service (QoS) is a term used to describe the level of performance a service gives to its users. In the case of V2I, the connection between all vehicles needs to be of a high QoS. Metrics of a connection with a high QoS include long connection duration, low end-to-end delay, and high packet delivery ratio [5]. A high connection duration is needed to have a meaningful interaction between two entities, losing connection before all data is transferred could prevent tasks from being completed such as driving in sync with other AVs. End-to-end delay refers to the time a piece of data takes to reach an entity once it is sent, high delays could cause instructions for a platoon an AV is in to change lanes before it does. When information is transferred between entities it is sent in multiple packets, a perfect 1:1 packet ratio means every piece of data sent was received. Once packets start failing to deliver, the reliability of that data decreases as pieces of it are missing, therefore the data could be unusable by the vehicle.

With many different companies creating their version of the AV, they could all have different visions and approaches on how to achieve communication and coordination. This creates a barrier that currently prevents coordinating AVs from advancing. Standardization is important as it sets the rules that allow an industry to operate efficiently and smoothly. Currently there no documentation exists which is accepted by the majority of AV developers that state the rules and procedures for coordination.

VI. Social impact and ethical aspects

SOCIAL Internet of Vehicle (SIoV) is a network of vehicles that share information of common interest with each other. The traditional SIoV layered architecture has three layers: application layer, network layer, and sensing layer. The network layer in SIoV architecture is responsible for the communication between V2V and V2I. This layer guarantees seamless connectivity through various communication technologies and is also responsible for security, QoS, and privacy. Due to the responsibilities, it includes various ethical implications. An ethical implication would include the type of information an AV can share. An AV sharing its vehicle and passenger details with another vehicle might be considered unethical depending on the purpose [15]. An example would be if law enforcement requested and received personal information relating to the destination and pathing of the vehicle. The number of interactions a vehicle would have during a journey could be in the hundreds, this makes it unviable for consent to be asked for from the passengers every time a request for information is received. This introduces the question of how can an AV decide who can access its information?

The safety of AVs requires them to handle unexpected situations by creating viable solutions. Situations such as slowing down when a person walks onto the road may be a simple problem of algorithmic nature, but when situations arise where the damage to the vehicle, or injures to the passengers and pedestrians can happen, the situation can become a problem of ethical nature. When exploring ethical decision-making, we can start by examining the trolley problem. It is a series of thought experiments where the dilemmas of whether to sacrifice one person to save a larger number are discussed. In the case of an AV, while it is traveling along a trajectory, a child might unexpectedly appear in its path giving the AV not time to brake or safely change direction. Two options would be to kill the child or change direction rapidly and collide with an obstacle that could kill the passengers. This creates the question of whether a person would be comfortable entering a vehicle that could decide to kill them? When we considering coordinating AVs, the dilemma would involve two vehicles entering each other's trajectory and an unavoidable crash will take place killing all passengers in both vehicles unless one vehicle sacrifices their passengers. The ethical implication is how do the vehicles decide which groups of passengers live or die [11]?

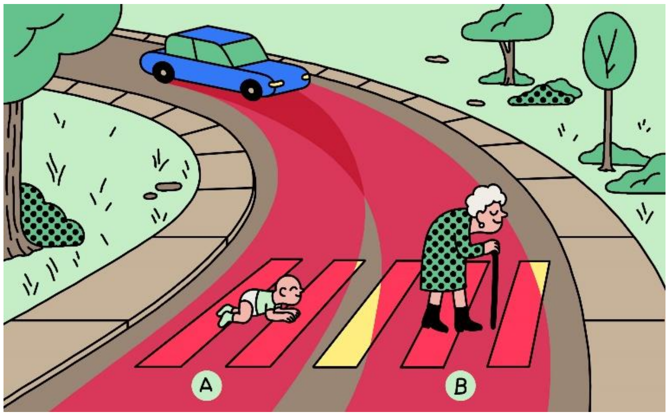

Fig. 3. A variation of the trolley dilemma involving a child and an elderly person. [27]

By utilizing V2V communication to allow coordination between emergency vehicles and other AVs on the road, relevant information can be shared to allow for faster reaction times and safer transit for rescue vehicles. This can be achieved by having the emergency service informed about the fastest route to the accident and preventing vehicles in the emergency services path from forming traffic jams [13].

There are an estimated 1.25 million deaths from traffic accidents annually in the world and 20-50 million non-fatal accidents. The consequences of this happening can cause a financial burden on the victims and their families as well as inflict emotional trauma on some [21]. With around 90% of all these accidents being caused by human error [22], taking the responsibility away from the driver and having a fully autonomous system take control would reduce the consequences stated. Although the impact of an autonomous system on its own would be greater than having the ability to coordinate with other vehicles, coordination still influences those figures. An example would be that two coordinating vehicles could evade a wrong-way driver without colliding with each other by planning a coordinated lane change maneuver [23].

VII. Visions of the Future

PREDICTIONS of the future are difficult to make due to the forever changing landscape of technology and innovation, take Popular Science's wire guidance system [26], although it seemed practical at the time, the vision of AVs quickly shifted from that idea. For coordinated AVs, many scientific bodies and organizations have stated that CAD is the future, with The European Commission reporting that cooperation, connectivity, and automation are not only complementary technologies; they reinforce each other and will over time merge completely [12].

A future vision of coordinated AVs involves the use of a Coordinated Automated Road Transport (C-ART) system. This vision believes that between today and the year 2050, there will be a drastic change in the transportation system along with the oncoming decades. This comes with the assumption that almost 100% of the vehicles on the road are automated and the C-ART controls the whole road transport network. In the year 2050, vehicles will no longer require a driver as they will transform and become fully autonomous. These vehicles will be connected to a network and coordinated for an optimal travel time. Passengers will be notified about journey-related details such as the estimated time to arrive at their destination. This future would give passengers the availability to work, read, or take a nap during the ride while allowing an individual to travel regardless of their physical condition or age. Once the journey is completed, the vehicle will automatically find a place to park and wait till another journey is requested. This vision reflects a threefold shift, vehicles shift from conventional to connected, then from connected to automated, and finally from automated to coordinated and automated [20].

Peter Davidson and Anabelle Spinoulas predicted that when all vehicles on the road are fully autonomous, vehicles will be able to travel at higher speeds with an increased density of vehicles on the roads due to the instant communication and reliable protocols between vehicles. They continued to say that it should also be possible to eliminate most traffic signals as we could rely on vehicles to communicate and provide minimal stopping. With the abomination of traffic signals, pedestrians would be able to notify their intention to cross the road to surrounding vehicles by using devices such as their phones, and V2V communication would allow all approaching vehicles to be aware of that situation [18].

VIII. Further Research Directions

Although this paper has discussed the many different aspects of AV coordination, there is still more research that has to be completed before it can be applied in the real world. We have established that due to the many different companies creating their version of the AV, different approaches to communication and coordination might be implemented. This could make it impossible for different brands of AVs on the same road to coordinate when they do not share the same solutions or communication methods. For communication, out of all the options, the most optimal and reliable method must be found through research. As discussed previously, options are to communicate purely through V2V or have a centralized messaging system, or a completely different method that has not been discussed. A set of solutions to coordination problems need to be agreed upon and implemented into all AVs. These solutions should also share the same designs to allow for compatibility.

Security is one of the most important factors to having AVs coordinate with each other, for the fact that messages received by the vehicle would affect the actions it performs. The legitimacy of the sender and message needs to be verified. In a similar way to how SSL certificates work with websites [24], an AV or infrastructure could be given a unique certificate issued by a trusted Certificate Authority (CA) when they are manufactured, and every time an AV receives information from a source, it can verify the sender through the CA. Although an information source can be verified as legitimate, what would happen if it got compromised and had messages sent out requesting AVs perform tasks which could be dangerous? Methods must be researched to allow AVs to decide whether a message to perform a task is viable.

As AVs slowly take over the driver's responsibilities, they will soon have to make ethical decisions. The question of how AVs should decide which group of passengers gets the worst outcome from a crash was previously discussed, that dilemma creates the need for ethics in coordination to be researched. In those situations, do the AVs bargain with each other, does the group with the highest survivability get the best outcome, would age and group size affect that decision? Also, as AVs will be responsible for sharing their sensitive information, this highlights the need to have a system in place to decide who can access that information. With a small number of circumstances where information would be shared, such as a group of AVs planning on platooning would share their journey pathing to allow for them to join or leave the platoon efficiently, a checklist could be used. Realistically, in the future, there could be too many reasons for sensitive information to be requested from an AV for a checklist, so the reason for when it should share information needs to be researched.

IX. Conclusion

THE goal of this paper was to understand the current extent of knowledge on the coordination of AVs. The discussion started from the beginning of the automobile to how they became autonomous. The current level of autonomy in AVs was appraised and placed at an SAE level of 2. Moving onto coordination, two important aspects of it were discovered: communication and solutions. Achieving coordination could be done through various communication methods such as V2V or using a central messaging system. Some coordination problems were discussed and the solutions to these problems depended on the level of autonomy of the AVs while they were coordinating. Although there were solutions to achieve coordination, there were still solutions to key challenges and ethical aspects that needed to be researched. Looking at predictions of AVs in the future, it was claimed that coordination would be a part of them. To conclude, after researching the topic, a beneficial direction to take when advancing AVs would be to further research and implement coordination.

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