How has the development of AVs influenced the way they are assessed for public safety, and how has their mass deployment impacted the safety of real-world roads?

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Abstract

The multi-development of autonomous vehicles (AVs) has made our transportation systems a breeze. They are a quick, simple, and efficient form of transportation, as well as providing flexibility and safety. However, this rapid pace of development of AVs has also provided many difficult challenges, including safety concerns, regulatory procedures, and ethical dilemmas. This paper will explore the historical evolution of AV technology from universities, small organizations, and current-day industry leaders that helped with the early stages of safety systems like Mercedes-Benz's Prometheus Project to modern AV industry leaders like Waymo. Additionally, the paper will provide all the financial pressures of AV innovation and safety, highlighted by major incidents by Uber and Cruise. Furthermore, the study dives into the mass development of AV safety regulations, including California's AV licensing program, NHTSA guidelines, and safety protocols such as UL 4600 (Standard for Safety for the Evaluation of Autonomous Products), Safety of Intended Functionality (SOTIF), and ISO 26262. By analyzing the progress and setbacks in AV innovation, this research aims to understand the comprehensive risks and opportunities of the widespread deployment of autonomous vehicles in the near future.

Introduction

The concept of autonomous vehicles (AVs) has been in the eyes of scientists, engineers, and futurists for a long time. While AVs became part of the public focus a few years ago, their development started a few decades ago. The journey for full autonomy started as early as the mid-20th century with General Motors' Firebird II [1], a concept car that envisioned a future where cars could be guided by electronic highways (highways during the late-20th century that were built with the initial stages of the toll collection system). Several decades later, in the 1980s, the modern concept of AVs started at Carnegie Mellon University (CMU), which implemented computer-integrated camera vision and sensor-based navigation [2].

In the 1980s and early 1990s, CMU's Navlab project provided further tests for the innovation of self-driving capabilities. One of its most significant achievements was the "No Hands Across America" campaign in 1995, which attempted a fully autonomous, 2500-mile, cross-country trip [3]. During the same period, Mercedes-Benz's EUREKA Prometheus Project (1987-1995) demonstrated advancements in AV technology by incorporating early computer vision and autonomous automation [4]. This project led to the development of Advanced Driver-Assistance Systems (ADAS) and the VaMP and VITA-2 concept vehicles, which navigated over 1000 kilometers on a Paris multi-lane highway while achieving speeds up to 130 km/h. These concept vehicles are the predecessors to the Mercedes-Benz 500 SEL model [5]. The ADAS demonstrated capabilities such as automatic lane changes, speed control, and vehicle tracking without any interference from the driver assistant. The enormous influence of these driver assistance systems, which eventually led to autonomous vehicles, created multiple competitions around the nation, leading to a race to see who could build the best, safest, and most reliable AVs.

By the early 2000s, AV development became a mainstream endeavor through competitions like the DARPA Grand Challenge. This government-led program presented multiple challenges, which consisted of driving many miles without any human intervention. These annual races from 2004 to 2007 led to the development of state-of-the-art technology that would win prize money, up to several million USD [6]. Due to the success of these contests, Mercedes-Benz and Volkswagen, among other large automakers, made significant investments in AV research, creating driver-assistance advancements that would eventually lead to commercially viable AV functions.

During the development of AVs, money and investments became a huge pressure on automotive companies that were trying to pursue self-driving technology. As technology for autonomous driving improved, the cost to develop it also increased. The race toward autonomy required billions in investments, having no room for budgets, and led to many automotive companies and tech companies backing out from economic aid for self-driving technology. With massive amounts of economic aid from the government and investments from private corporations and technology companies, the AV industry was able to withstand most of the stress there was. Currently, Waymo, initially a Google project, has received and spent over $5 billion on AV development, while Cruise has received over $10 billion from General Motors, Honda, and SoftBank [7] [8].

Even though massive investments were offered to present a hopeful picture of AV advancement, it also brought a new kind of pressure that arose from investor expectations and the need to depend on large amounts of spending. Due to the pressure to speed up development, companies frequently placed cars out onto public roads before safety features were completely developed. The combination of this financial pressure and severe competition in the market has unpredictable and negative impacts that could change the direction of AV development.

Today, the landscape of AV development is defined by major companies like Waymo, Tesla, and Zoox. However, the rapid pushing of these developments did not come without serious challenges. High-profile accidents, such as the 2018 Uber AV incident in Tempe, Arizona, and Cruise's 2023 pedestrian-dragging incident in San Francisco, have raised multiple concerns about the safety of self-driving vehicles and regulatory oversight [9] [10]. These tragedies not only ignited public and regulatory inspection but also forced some companies to pause, pull back, or reevaluate their approach to autonomous driving.

As AV technology continues to advance, it is essential to understand its historical evolution to contextualize its present challenges and future potential. From early experiments and government-funded prototypes to billion-dollar corporate investments, the path to autonomy has been shaped by innovation, ambition, and rapid expansion. However, as history has shown, rapid advancements, especially during financial troubles, can lead to unintended and unwanted situations. By tracing the start of the AV industry to its modern-day implementation, this research seeks to explore not only the milestones and breakthroughs but also the regulatory improvements/gaps and testing limitations that now define the industry. Through this breakthrough, we can determine what is best for us and what it would take to create a safe, responsible, and reliable autonomous future.

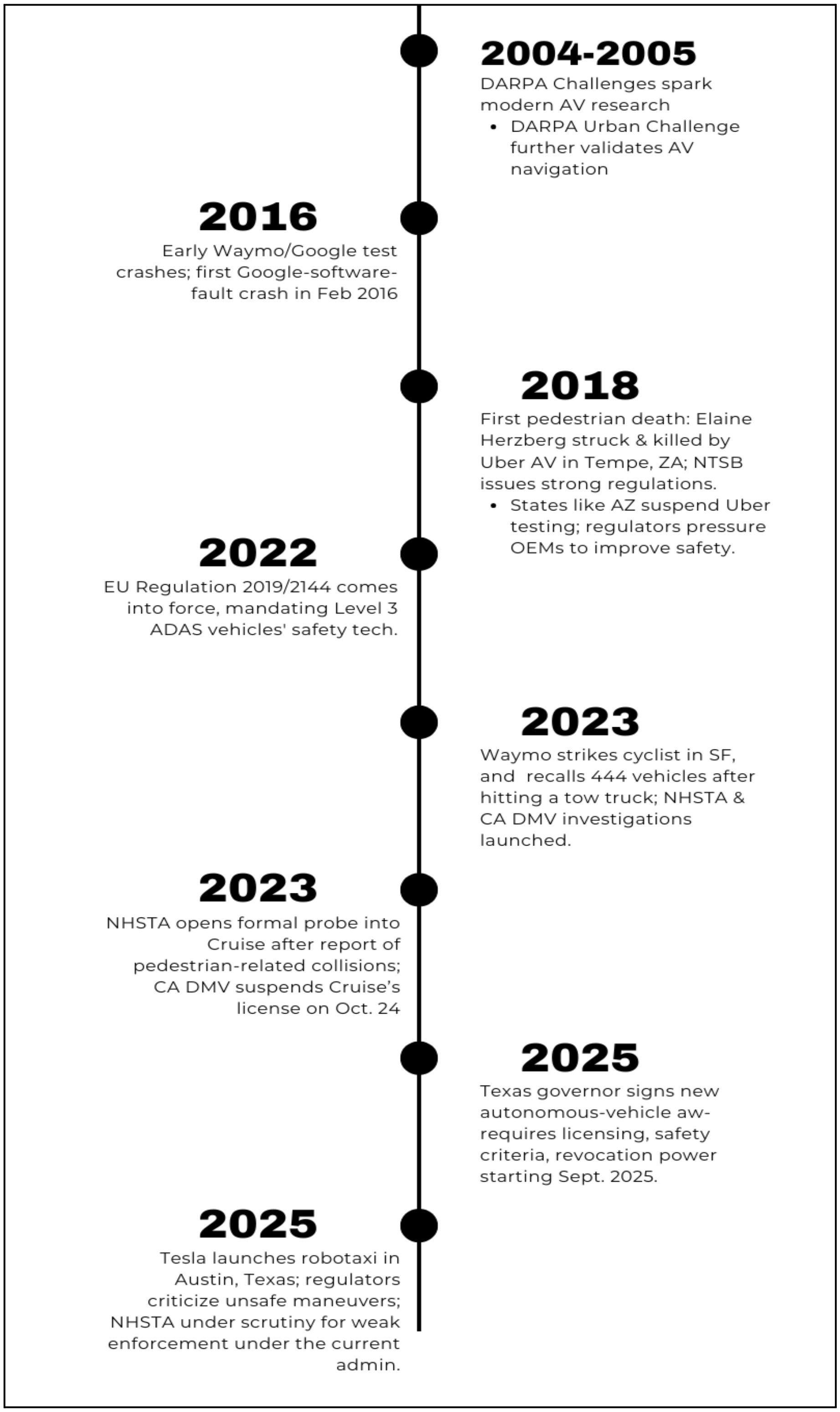

Figure 1. Timeline from 2000-2025, showing the developments of AV regulators, and major AV incidents with responses.

Background

Autonomous vehicles usually undergo various amounts of testing and image training, each designed to evaluate their safety and performance progressively. Most AVs are tested and trained on closed-track environments where all sorts of conditions like road conditions, traffic, and obstacles are in the most ideal state and controlled. Facilities like MCity at the University of Michigan simulate the urban environments on their closed tracks, allowing companies to experiment with their vehicles in a safe, predictable, and controlled environment [11].

Once the foundational testing is complete, developers transition to the geo-fenced testing environments, where AVs operate in a limited and pre-mapped real-world area with predefined boundaries to maximize results. A notable example of geo-fenced testing is Waymo's liability development in the San Francisco Bay Area, where vehicles were restricted to certain neighborhoods and routes that are specifically optimized for AV performance [11]. Companies also conduct tests on specific highways, where the driving environment is relatively structured and easier for the AVs to navigate. Eventually, some AV manufacturers explore generic, low-restriction testing, allowing vehicles to operate anywhere on Earth, including dense urban centers and complex traffic patterns with little to no human intervention.

This progression from controlled environment testing to the real world reflects both technological confidence and errors with the ongoing tensions for safety and reliability, as later illustrated by several high-profile AV incidents. To guide this development, various safety frameworks and industry standards have emerged. ISO 26262 addresses the functional safety of electrical and electronic systems in vehicles, establishing processes for identifying and mitigating risks due to system failures [95]. UL 4600, developed by Underwriters Laboratories, focuses specifically on the safety of autonomous products, especially where no human operator is present. It provides a systems-level approach emphasizing transparency, traceability, and validation without reliance on a human driver [96]. Additionally, SOTIF complements ISO 26262 by addressing situations where the system behaves as intended but leads to unsafe outcomes due to environmental distractions, sensor limitations, or unexpected interactions [97]. Together, these standards create a baseline for AV developers and regulators to design, test, and validate autonomous systems as they progress into complex real-world situations.

Methodology

This research used a combination of case study analysis, comparative review, and regulatory landscape assessment to understand the development, risks, and policy changes surrounding autonomous vehicles. To gather most of the information, I relied primarily on open-access government documents, news coverage from credible technology and automotive sources, and official agency press releases. Government sources such as NHTSA, NTSB, and CA DMV were emphasized, and were chosen due to their authority in transportation safety, incident reporting for my case studies, and regulatory oversight. Additionally, reputable technology journalism sources like TechCrunch, The Verge, IEEE Spectrum, and Reuters were used to track company and victim statements. The sources were accessed through new aggregators such as Google News and by following hyperlinks related to the incidents. It is also important to note that not all internal company data was accessible for this research. Limitations like this exist in my paper due to proprietary AV testing logs and confidential simulation performance reports. As a result, the scope of this paper was solely on the focus of publicly available sources and post-incident investigations rather than having a predictive model.

Case Studies

1. Uber Pedestrian Death Incident

On the night of March 18, 2018, a self-driving Uber test vehicle struck and killed Elaine Herzberg, a 49-year-old pedestrian, in Tempe, Arizona. This incident was known as the very first fatality from a fully self-driving vehicle. The tragedy of this incident not only halted Uber's AV testing but also marked an enormous turning point for how the public and regulators viewed autonomous vehicle safety [12].

1.1 Events of Crash

The vehicle involved was a Volvo XC90 SUV, which was equipped with Uber's self-driving hardware and software and operated in autonomous mode with a safety driver behind the wheel. The SUV was operated by the Advanced Technologies Group (ATG) of Uber Technologies, Inc., which had modified the vehicle by installing a proprietary developmental automated driving system (ADS) [13]. The SUV, driven by a 44-year-old woman, an Uber Technologies employee, was making its second lap around a designated test route that went through N. Mill Avenue. The SUV had been driving in the right lane at a constant speed of 45 mph for 19 minutes when it approached the crash area while still in autonomous mode. Herzberg was walking with her bicycle across a multi-lane road of N. Mill Avenue at night, not on a provided crosswalk, when the Volvo struck her at approximately 39 mph, leading to her death, without swerving or braking (see Figure 2) [14].

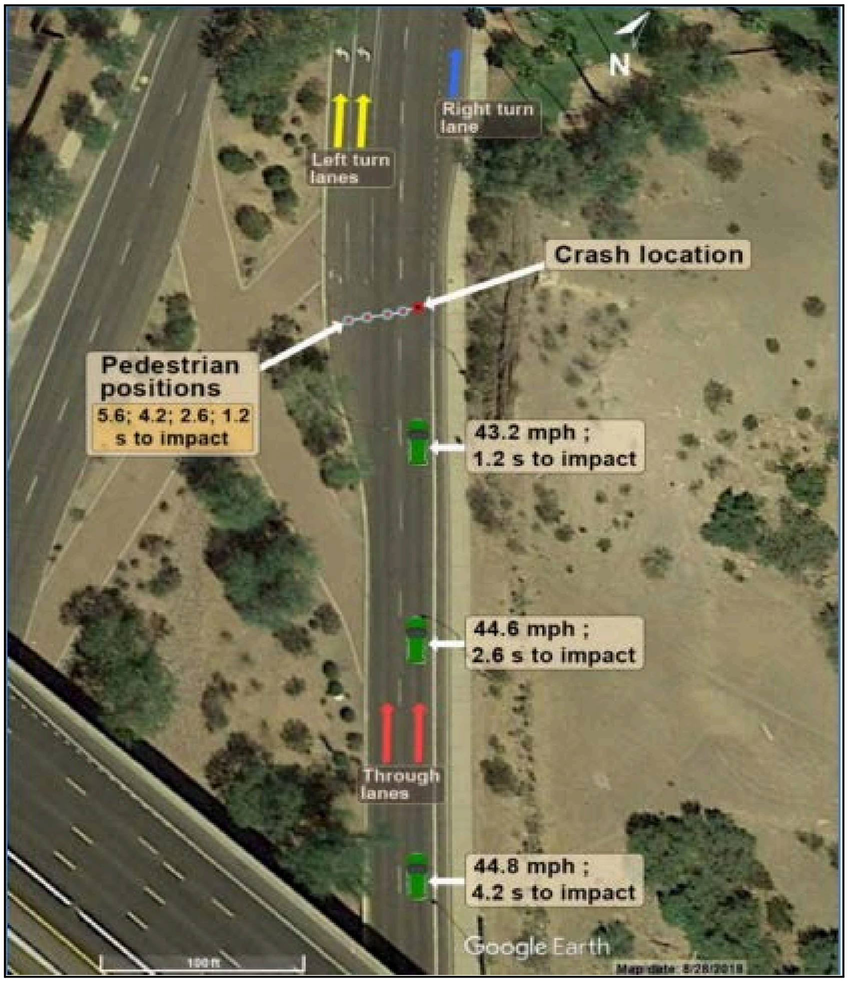

Figure 2. Aerial view of crash location showing pedestrian path as she crossed N. Mill Avenue and movement and speed of SUV at three points before impact. The pedestrian's path shows her position from initial detection until impact. [14]

1.2 Uber's ATG Automated Driving Systems

The Volvo XC90 was fitted with Uber's proprietary developmental ADS, which comprised multiple systems for continuous vehicle control. The LiDAR (Light Detection and Ranging) system, manufactured by Velodyne and mounted on the vehicle's roof, provided a 360-degree viewing angle scanning with a detection range of up to 100 meters. A sum of eight radar units offered dual-mode scanning, consisting of long-range (up to 180 meters) and medium-range (up to 65 meters), for object classification and motion tracking. The camera system included eleven cameras positioned to be able to look 360 degrees around the vehicle. These high-definition cameras offered long-range stereo imaging, medium-range object detection, and traffic signal recognition.

Additionally, the vehicle was integrated with ultrasonic sensors for near-field obstacle detection, a global positioning system (GPS) for route tracking, a long-term evolution (LTE) antenna for communication, and an inertial measurement unit (IMU) to monitor the acceleration and velocity of the vehicle. These systems were designed to function all in sync, continuously feeding data into the ADS for autonomous decision-making. Despite all these advanced sensor attachments, the ADS still failed to classify Herzberg as a pedestrian in time accurately, and no signs of evasive maneuver or braking were observed before impact. [14]

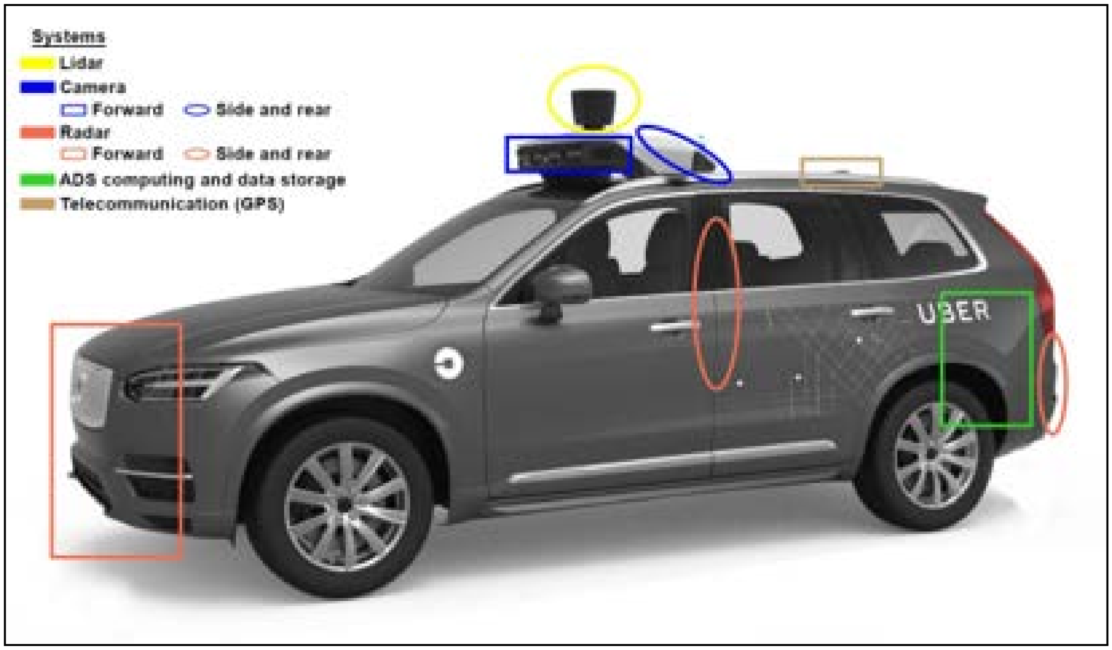

Figure 3. Location of the main ADS sensors equipped on a 2017 Volvo XC90. [14]

1.3 Consequences/Implications

1.3.1 Legal and Regulatory Outcomes. Federal and state authorities launched multiple investigations into this incident. The National Highway Traffic Safety Administration (NHTSA) sent a Special Crash Investigation team to Tempe, and the National Transportation Safety Board (NTSB) opened a field investigation. In the final report, the NTSB concluded that the crash was caused by "the failure of the vehicle operator to monitor" the road, while she was distracted by a phone, and cited Uber's "inadequate safety culture" and Arizona's lax oversight as contributing factors [15]. The report noted that although the pedestrian was detected, the system did not brake because Uber had disabled the Volvo's factory automatic braking in self-driving mode [16]. The NTSB issued recommendations to NHTSA, state governments, and industry, including requiring testers to submit safety assessments before testing and Uber to implement a formal safety-management system [14].

On the legal front, Uber settled civil claims with Herzberg's family, averting a lawsuit. Prosecutors in Arizona determined there was "no basis for criminal liability" for Uber as a company [17]. The safety driver, Rafaela Vasquez, was charged with negligent homicide in 2020; she eventually pleaded guilty to a reduced charge of endangerment in 2023 and received probation [18]. Arizona Gov. Ducey suspended Uber's testing permit immediately after the crash, calling it "an unquestionable failure" to meet public safety expectations [19]. Hearing about the incident, the California DMV announced Uber would not be able to renew its autonomous-vehicle testing permit, and Uber itself said it would not reapply [20].

1.3.2 Impact on Uber's AV Program and Business Strategy. Uber's immediate response was to pull back sharply. The company suspended all its self-driving tests across North America (in Phoenix, Pittsburgh, San Francisco, Toronto, etc.) [19]. Internally, Uber overhauled its safety processes by retraining all operators, implementing stricter in-car monitoring, and reviewing its systems in light of the NTSB findings [17]. In the longer term, Uber rethought its AV ambitions. By late 2020, Uber agreed to sell its self-driving division to startup Aurora, receiving a 26% stake in the combined company. This deal was explicitly framed as accelerating Uber's path to profitability by letting it refocus on core ride-sharing and delivery services. In effect, Uber transitioned from trying to build autonomy in-house to partnering with specialists. Management insisted profitability, not the crash alone, drove this decision, but the incident had underscored how costly and difficult large-scale AV development could be [21]. Recently, in 2025, Uber has shown signs of getting reinvolved in its autonomous division. Uber, with MayMobility, has decided to launch robotaxis in different major cities [22].

1.4 Discussion

The 2018 Uber incident marked a significant setback in public perception and regulatory image regarding the deployment of autonomous vehicles. As one of the first companies to test fully autonomous self-driving technology on public roads, Uber's ambition to lead the industry came with a risk. The NHTSA responded quickly and appropriately by initiating a thorough investigation and recommending stricter oversight. While initial assumptions placed blame on the jaywalking pedestrian, subsequent analysis revealed that liability rested in Uber's hands, whose systems failed to detect and react appropriately. This case reinforced the principle that AV developers assume full responsibility for operational safety during public road testing. The incident highlighted key areas for improvement, including the need for better training of in-vehicle safety operators, particularly during night operations, and for rigorous hardware system checks before each test deployment. These measures are critical to prevent similar tragedies and to restore public trust in the autonomous industry.

1.4.1 Public and Media Reaction. The fatality shook public views on self-driving vehicles, especially given that this was the first pedestrian death caused by an AV. News reports explained it as a pivotal moment for self-driving cars – "the moment many people in the car industry have feared," as one analyst puts it [19]. News media like the BBC highlighted the NTSB findings that Uber's "safety culture" was at fault and described the crash as "mostly caused by human error" [17].

Public opinion polls taken afterward showed a marked decline in trust toward AVs, with many respondents expressing hesitation or outright opposition to sharing roads with AVs. Surveys reflected shaken confidence: a spring 2018 AAA poll found 73% of Americans were "too afraid" to ride in a self-driving car, up from 63% before the Uber incident occurred [23]. Industry voices continued to weigh in; Waymo's CEO stated that his cars would have been able to handle the scenario safely, while Lyft's president said the crash "should give everyone pause" but cautioned that over-hasty delays in AV development could cost lives [24]. Safety and labor groups used the incident to demand stronger oversight for the regulations of AVs. The Amalgamated Transit Union flamed regulators for issuing a "rubber stamp" to AV companies and urged rewriting federal AV legislation to mandate robust safety plans. In short, public reaction combined outrage and fear with calls for stricter regulation, highlighting the fragile trust in this rapidly developing technology.

2. Cruise Pedestrian Dragging Incident

A robotaxi (GM Bolt EV) owned by Cruise LLC struck and dragged a pedestrian around 20 feet in San Francisco on October 2, 2023. Reports initially described that a human-driven car hit the woman, throwing her into the autonomous vehicle's path. The Cruise AV braked but did not remain stationary and dragged the individual forward under its wheels [25]. Federal and state regulators launched multiple inquiries into Cruise's response and reporting of this crash.

2.1 Events of Crash

On the night of October 2, 2023, at approximately 9:30 PM, a Cruise autonomous vehicle was involved in a serious pedestrian incident at the intersection of 5th Street and Market Street in downtown San Francisco. Cruise's vehicle, the Chevrolet Bolt EV, owned by GM Motors, was the vehicle that was responsible for dragging the pedestrian after another car had initially struck the pedestrian. The other vehicle, which was a Nissan Sentra, was human-driven and was standing beside the Cruise AV, both obeying a red light, waiting to pass Market Street to East Fifth Street (Figure 4). Once the light turned green, the Nissan went through the intersection and struck the pedestrian who was walking across the street when the walking signal displayed "do not cross" (Figure 5). The Nissan was able to speed up and reach up to 21 MPH before striking the pedestrian (who had not been publicly released), who got "launched" into Cruise's lane. The

Cruise vehicle, on the other hand, was traveling at about 17 mph and around a car's length behind the Nissan driver. Cruise's AV systems initially detected an "unidentifiable object" on the road that caused it to apply its brakes for a short period. The final collision between the Cruise and the pedestrian was at 18 mph (Figure 6). Eventually, the Cruise's systems were able to detect a "minor collision," causing it to initiate a pulling over mechanism, thus running over the pedestrian and dragging them for another 20 feet. [26]

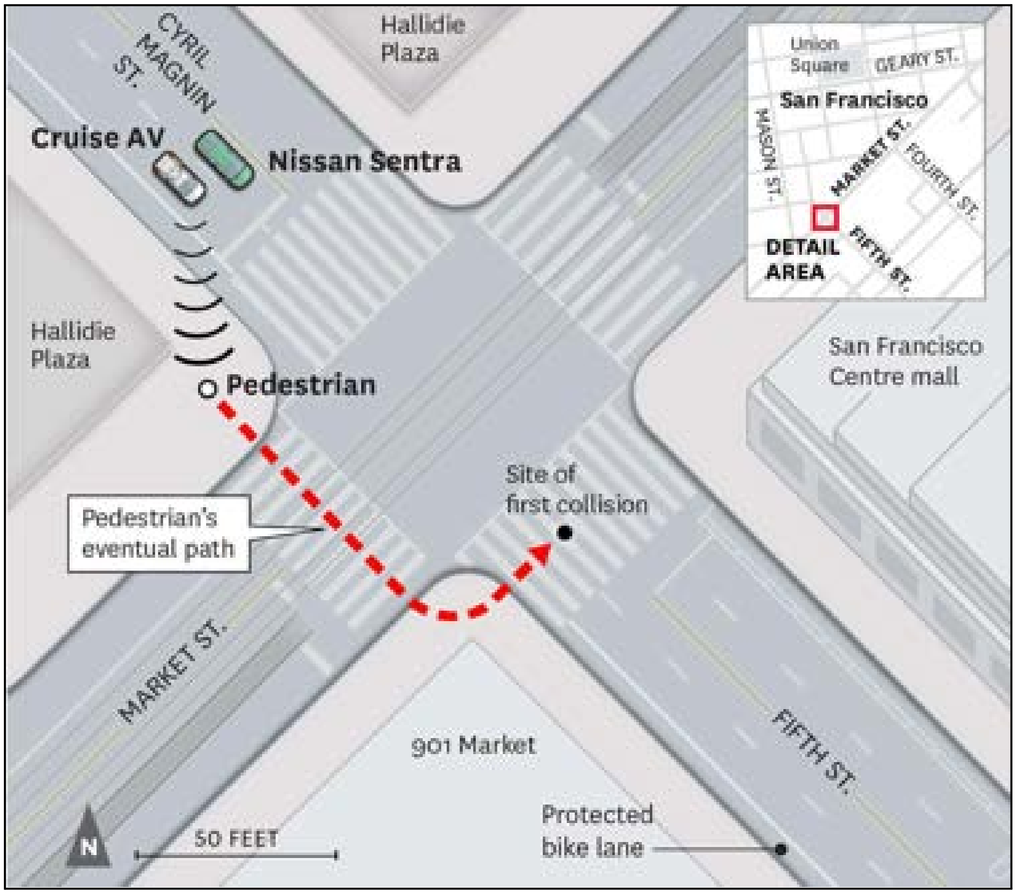

Figure 4. Initial conditions of the Cruise incident with the Cruise AV and Nissan Sentra driver being held at a red light before crossing the intersection. Which also shows the pedestrian's eventual path leading to the accident. [26]

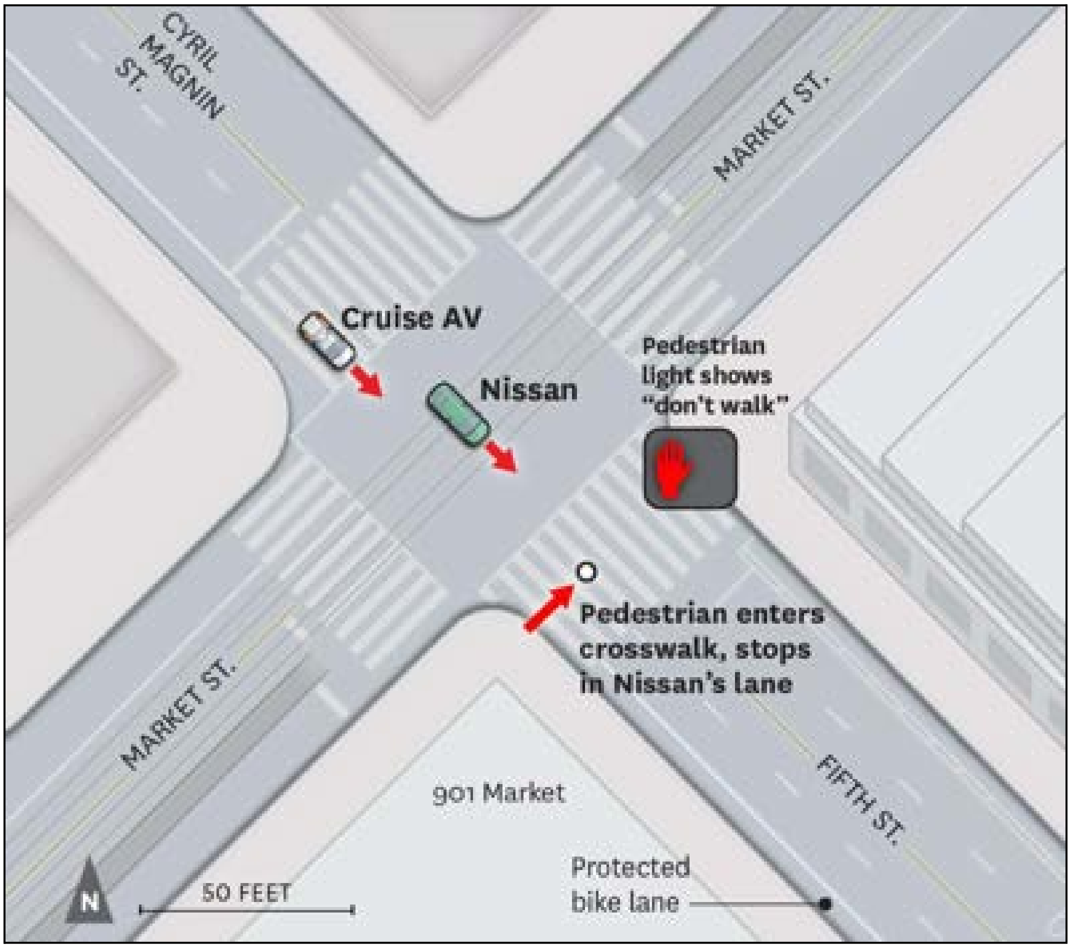

Figure 5. Cruise AV and Nissan driver speeding up after receiving a green light, and a pedestrian entering the street with a “don’t walk” signal. [26]

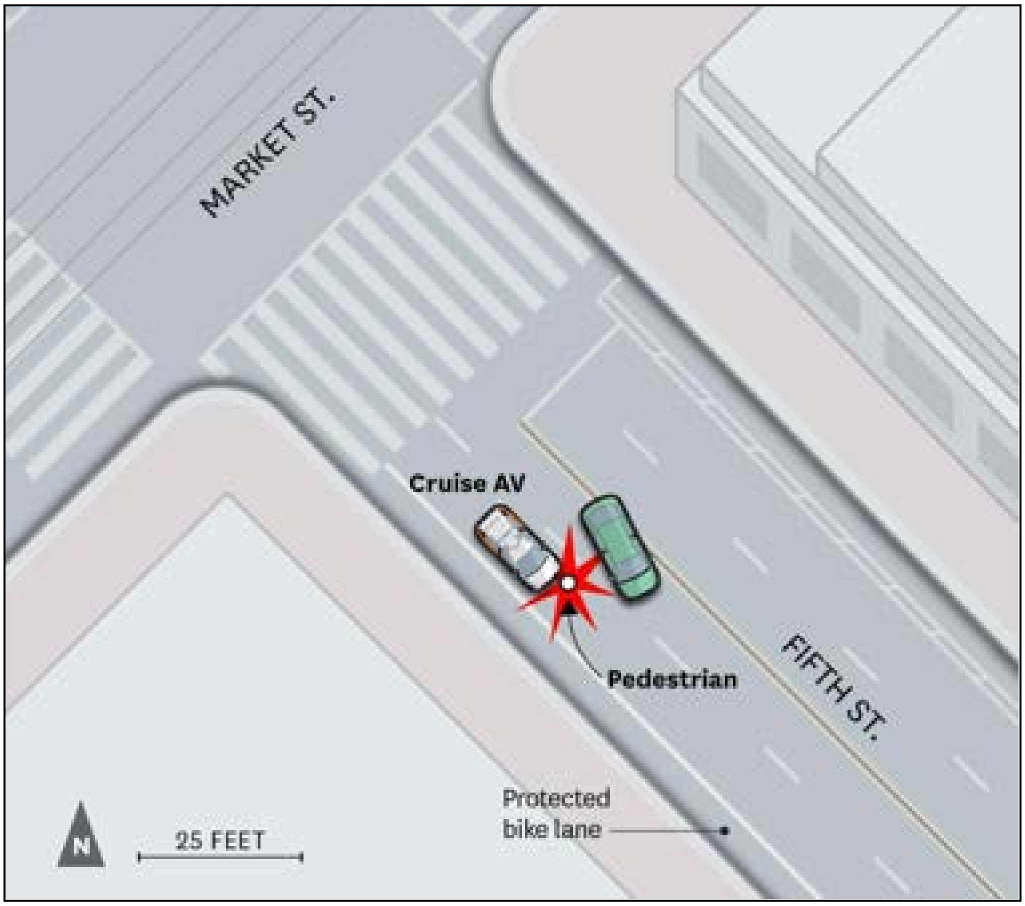

Figure 6. After the Nissan launches the pedestrian into the Cruise AV's lane, the Cruise AV does not detect the pedestrian and collides with them. [26]

2.2 Cruise's Autonomous Driving Systems

Cruise's autonomous Bolt EV vehicles carry a full 360-degree sensor array of LiDARs, radars, cameras, and short-range proximity sensors. According to GM, the Cruise AV utilizes multiple Velodyne Puck LiDAR units, numerous automotive radars, and an array of video cameras for perception [27]. The Cruise AV carries five rooftop LiDAR sensors, roughly 16 cameras, and about 21 radar units. Additionally, Cruise utilizes a unique set of Articulating Radars (ARAs), featuring one in the rear and two on each side of the car, positioned beside the A-pillar.

The number and placement of the sensors around the vehicle are chosen for a full 360-degree coverage. GM describes the Cruise AV as having five roof-mounted LiDARs, a sensor module that also contains many of the cameras and radars (as seen in Figure 7) [28]. The 16 cameras are positioned to cover the front, rear, and sides, providing a 360-degree view of the surroundings and road. The 8 fixed long-range radars are tucked into the bumpers and grill, and the 10 short-range radars are on bumper edges. The 3 articulating radar units are visibly mounted near the front A-pillars and rear roof.

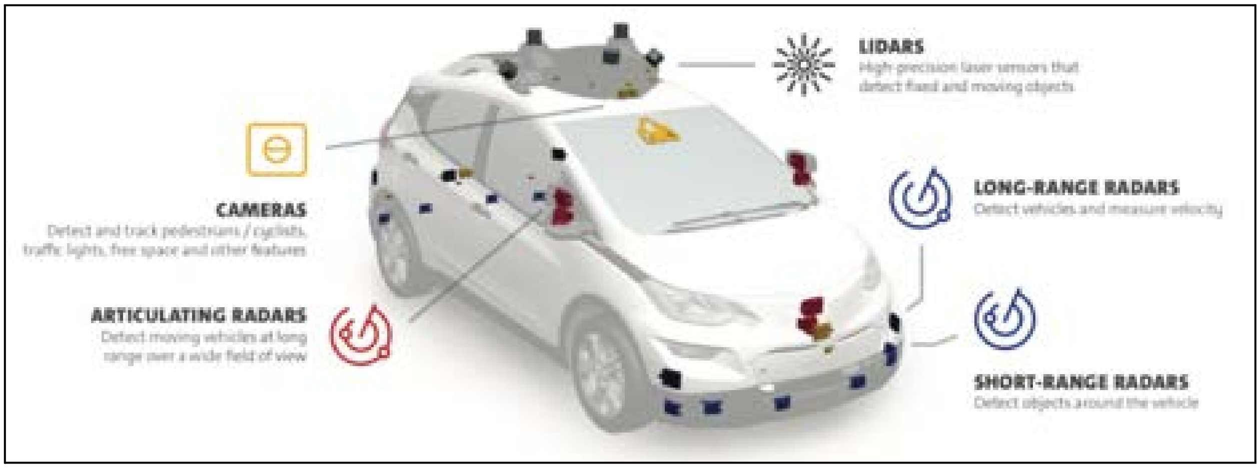

Figure 7. Locations of hardware on the Cruise AV, displaying the 5 mounted LiDARs, cameras, sensors, and the articulating radars on both sides of the car. [27]

2.3 NHTSA's Actions in Cruise's Incident

2.3.1 Preliminary Evaluation. On October 20, 2023, NHTSA's Office of Defects Investigation (ODI) opened a Preliminary Evaluation (PE23-018) into Cruise. The NHTSA letter explicitly stated "allegations of ADS-equipped vehicles operated by Cruise…not exercising appropriate caution around pedestrians," potentially raising collision risk [29]. NHTSA requested incident video and ADS data under its standing crash-reporting orders.

2.3.2 Failure of Correct Evidence. On September 30, 2024, NHTSA announced a Consent Order with Cruise for failing to fully report the October 2 pedestrian crash. NHTSA found that Cruise submitted crash reports to regulators that omitted the pedestrian-dragging detail [30]. The Consent Order imposes financial and compliance penalties: Cruise will pay a $1.5 million penalty and must submit a safety "corrective action plan" to improve its crash-reporting and safety processes. The order also mandates enhanced oversight: Cruise must regularly report vehicle miles traveled, number of vehicles, software updates, traffic citations, and other safety metrics to NHTSA. Basically, placing Cruise on a restraint makes them unable to make any sort of changes to their vehicles or hardware without the consent from NHTSA.

2.4 Regulators Reaction

2.4.1 California Regulators. The California Department of Motor Vehicles (DMV) immediately suspended Cruise's permits to deploy and test driverless cars. The DMV cited "performance of the vehicles" and specifically Cruise's misrepresentation of safety information as grounds for suspension [31]. The DMV statement invoked regulations allowing suspension whenever a manufacturer's vehicles "are not safe for the public's operation" or if the "manufacturer has misrepresented any information related to safety" [31].

The California Public Utilities Commission (CPUC) likewise pulled Cruise's license to carry robo taxi passengers. CPUC documents noted that the DMC's suspension of Cruise's driverless testing permit automatically suspended Cruise's Transportation Charter-Party (TCP) passenger permit [32]. The CPUC also opened its inquiry into Cruise's disclosures about the October 2 crash. CBS News states that Cruise later offered to settle the CPUC investigation with a $75K payment for failing to fully disclose details about the incident [33].

2.4.2 Federal Enforcement. On November 14, 2024, the U.S. Attorney's Office announced a Deferred Prosecution Agreement with Cruise. Cruise pleaded guilty to a single criminal count of providing a false report to NHTSA and agreed to a $500,000 fine. The Department of Justice (DOJ) press release states that Cruise knowingly omitted the pedestrian-dragging in its crash reports. Cruise faked records to influence the ongoing NHTSA investigation into the October 2 crash. The agreement describes the crash similarly to NHTSA's account: a Cruise vehicle "operating without a driver ran over a "pedestrian," who had been thrown into its path, then dragged the victim. U.S. Attorney authorities and the Department of Transportation Office of Inspector General (DOT-OIG) emphasized that companies "must be fully truthful in their reports to their regulators" to protect public safety [34].

2.5 Financial Failures

The October 2, 2023, incident involving the Cruise robotaxi in San Francisco not only hurt the company's reputation. This incident led to a cascade of financial consequences that destabilized Cruise's operations. In the aftermath of the crash, Cruise's parent company, General Motors (GM), faced growing pressure from regulators, investors, and the public, which triggered a reevaluation of Cruise's long-term operational costs [35].

2.5.1 Operational Shutdown. Near the end of 2024, Cruise voluntarily suspended all driverless operations across the U.S., halting its services in San Francisco, Austin, Houston, Phoenix, and other cities. This initiative, though necessary for public safety and trust, had severe financial implications. The company had invested billions into scaling its AV testing and deployment network, with operating costs surging due to the high employee headcounts, fleet management, and infrastructure [36]. According to reports, Cruise was burning approximately $2 billion per year and had not yet generated meaningful revenue. The sudden pause in operations meant an instant revenue freeze without a corresponding reduction in fixed expenses, increasing the company's cash burn rate [35]. Since GM's acquisition in 2016, Cruise has lost over $8 billion, and the trend shows a near-zero loss in 2017 to approximately $1.9 billion in 2023 (Figure 8). In response to this massive loss, GM leadership took decisive action. In early 2024, GM announced a $1 billion annual budget cut for Cruise and projected to halve its AV spending from $2 billion to $1 billion by mid-2025 (the AV spending includes their own ADS systems like Super Cruise in their manufacturing vehicles, as the numbers are shown in Figure 8) [37].

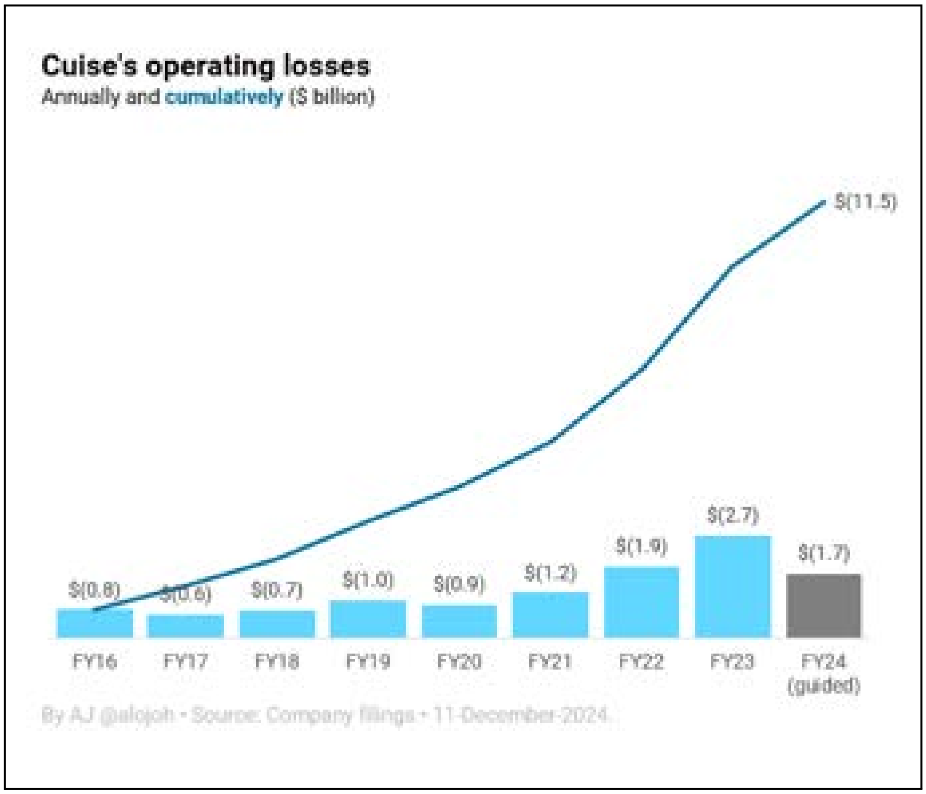

Figure 8. Graph showing the trend of increasing cash burn for Cruise. Starting from less than a billion dollars in 2016, the company had a cumulative loss of $11.5 billion in 2024. [38]

3. Amazon-owned Zoox also faces shifting incidents

On April 8, 2025, Zoox's Zoox L5 robotaxi, an electric 4-passenger, bidirectional vehicle, was involved in an accident with a human driver in Las Vegas, Nevada. The accident occurred due to an inaccurate prediction from Zoox's perspective, not being able to react in time to the human driver [39]. The crash on April 8th had no injuries to either party, and both vehicles had minor damage. Another incident occurred on May 8, 2025, when an unoccupied Zoox robotaxi was yielding at an intersection and was struck by a low-speed electric scooter, injuring the rider slightly [40]. The Zoox robotaxi had no way to avoid this incident, but made it worse by not being stationary and instead continuing on its path, then pulling over [41]. They were fortunate not to have another pedestrian dragging incident similar to Cruise's incident. Both of these incidents resulted in the voluntary recall from the company Zoox and paused operation until all of the Zoox robotaxis were software updated [42].

3.1 Events of Crash

3.1.1 Las Vegas Human Driver Incident. On April 8, 2025, the accident occurred in Las Vegas, near the Las Vegas Strip, a location with extremely busy streets. The Zoox robotaxi was going through its geo-fenced area, and a passenger vehicle was heading towards the robotaxi at 40 mph from a perpendicular driveway. The Zoox robotaxi's ADS system predicted that the vehicle would maintain its speed and continue through, and did not predict anything else. The prediction proved to be false as the human driver came to a complete stop and the Zoox robotaxi was unable to avoid the contact due to a mishap of prediction, despite subsequently braking and steering right to avoid a collision [43].

3.1.2 San Francisco Scooter Incident. On May 8, 2025, a person operating an electric scooter collided with a stationary Zoox robotaxi. This collision occurred on a busy intersection within San Francisco's South of Market neighborhood, specifically where 11th and Bryant Streets meet, near Division Street, typically an area known for its multidirectional traffic flow and dense pedestrian population [44]. The Zoox robotaxi was stationary at the intersection, yielding, checking for any pedestrians crossing. At that moment, an electric scooter rider collided with the vehicle, sustaining minor injuries, but no immediate harm occurred beyond the fall. Zoox's software misinterpreted the collision and continued the turn before stopping [42]. Zoox personnel were quick to respond to the scene of the incident and provided medical attention for the rider, which was declined [41].

3.2 Zoox's Hardware Systems

3.2.1 Vehicles in Operation. Zoox's AV fleet consists of two types of vehicles: a facelifted Toyota Highlander and the custom Zoox L5 robotaxi [46]. The L5 is a fully-electric "pod"-shaped vehicle that can carry up to four passengers face-to-face. It is bidirectional (which means it has no fixed front or back) and can drive equally well in either direction at speeds up to 75 mph [46]. The robotaxi has no steering wheel or pedals since it is designed for fully driverless operation, meaning it is not even able to be tested under physical driver suspension. Both the L5 and the facelifted Highlanders use identical sensor and compute packages, enabling data collection and testing under driver suspension (only for Toyota). [47]

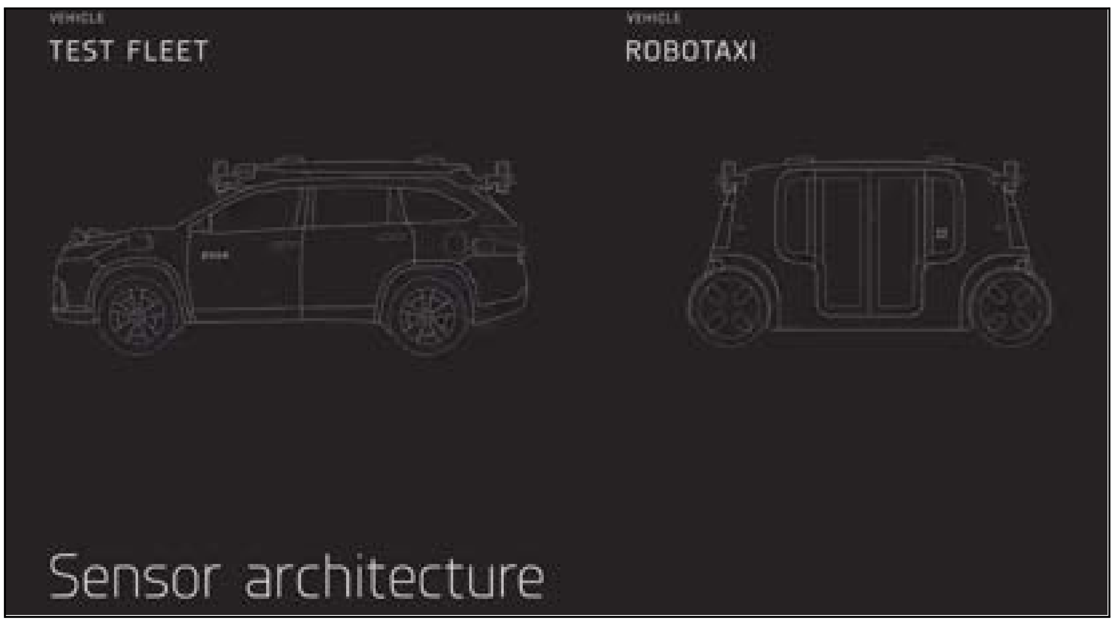

Figure 9. Zoox's fleet of robotaxis. The left shows the Toyota Highlander, and the right shows the Zoox L5 robotaxi.

3.2.2 Hardware & ADS. Zoox vehicles carry a comprehensive 360-degree sensor suite. According to Zoox technical disclosures, this includes multiple LiDAR units, short/long-range radar, high-resolution color cameras, and Long-wave Infrared (LWIR) cameras [46]. The sensors are mounted in four pods at the corners of the vehicle, each with roughly a 270-degree field of view [46]. In total, the vehicle has dozens of sensors: for example, outside analysis notes Zoox employs four LiDAR sensors plus an array of camera and radar sensors (Figure 10) [48].

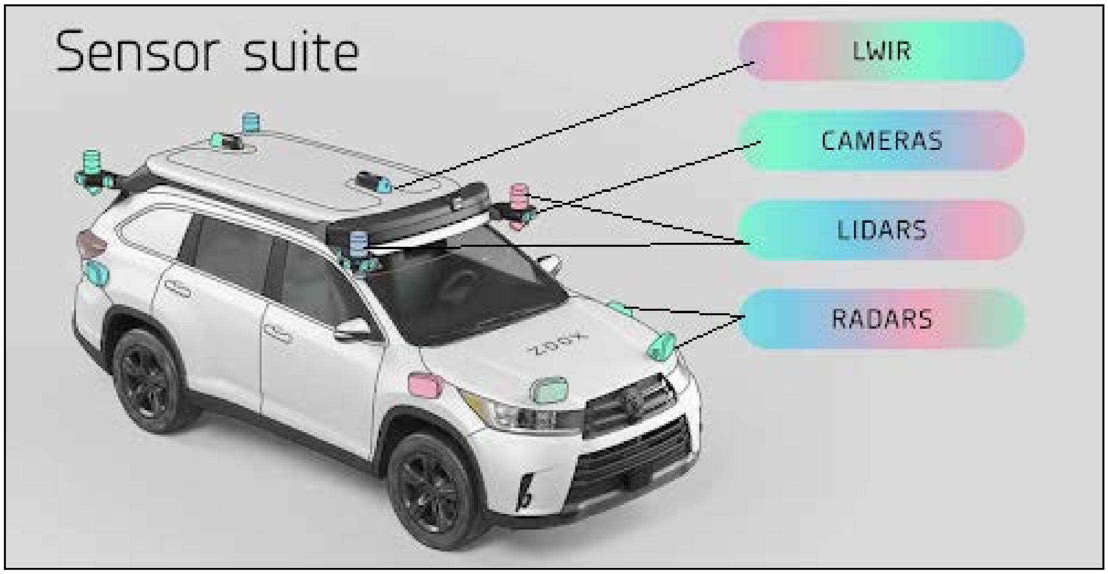

Figure 10. Location of all Hardware equipment on Zoox's Toyota Highlander unit. [49]

3.3 Zoox's Immediate Reactions

Following the two incidents previously introduced for Zoox, the company has implemented immediate responses. Following the April 8 crash, Zoox immediately paused all driverless testing across its geo-fenced areas and launched an internal review. Simulations confirmed that the issue occurred only at higher speeds, so testing resumed in slower zones while excluding the Las Vegas route above 40 mph. By mid-April, Zoox implemented a software fix in which updated ADS versions were rolled out to all 270 affected vehicles by April 17. Similarly, after the May 8 San Francisco crash, Zoox halted testing, provided data/video to regulators, and issued another recall to improve pedestrian and scooter detection [50].

Zoox's ability to implement vehicle recalls immediately demonstrates that they are not trying to go out of business due to accidents that may not have been entirely their fault. However, by being exposed to previous incidents that have put companies out of business, such as the Cruise incident, Zoox finds ways to solve its issues and faults in a matter of seconds. For example, Zoox's AV stack begins by fusing the sensor inputs to detect and classify all road users and obstacles. Therefore, making it the state-of-the-art machine learning model running on board to process camera, LiDAR, and radar data and produce a real-time bird's eye model of the environment [51].

3.4 Consequences/Implications

3.4.1 Regulatory Action. Zoox filed mandatory reports to U.S. regulators for these crashes. In May 2025, Zoox submitted a Part 573 Safety Recall Report for the Vegas crash, explaining that its ADS “may make an inaccurate prediction” when another vehicle slowly approaches from perpendicular streets and stops [52]. This defect led to the voluntary recall of the older software (before the April 17 update) to prevent such mispredictions. Likewise, a similar recall was issued after the San Francisco incident to improve how the AV tracks very near pedestrians and scooters [42]. Earlier in 2025, Zoox had already recalled 258 vehicles for an unrelated hard-braking software issue [39]; NHTSA has since closed its case of that braking issue [53]. No legal penalties or lawsuits have been reported; thus, regulators have largely overseen compliance via recalls and reporting. Zoox’s public statements emphasize that it immediately informed police/regulators after each incident, which is most likely why Zoox was able to stay away from huge headlines that may affect the company’s reputation, leading to bankruptcy [54].

3.4.2 Zoox’s Responsible Operations and Perception. Industry commentary notes that Zoox’s swift recalls demonstrate an ongoing effort to address safety gaps, even as autonomous programs face public scrutiny. For example, the financial news outlet Finimize observes that Zoox’s recalls highlight “the complexities of operating driverless vehicles under regulatory scrutiny” and warns that “ongoing safety issues could hinder broader adoption and impact investor confidence if not addressed” [53]. Zoox’s owner, Amazon, is reportedly using these fixes to protect its investment and maintain consumer trust. So far, analysts see the incidents as manageable setbacks, and Zoox continues preparing for limited robotaxi service in Las Vegas and other cities, but regulators and the public are close at watch.

4. Waymo's Deal with a Cyclist

On February 6, 2024, there was an incident report about a Waymo autonomous driver colliding with a cyclist in San Francisco. The collision didn't seem to be life-threatening, and the investigation started right away [55]. The issue with autonomous vehicles getting involved in even the most minor accidents is that they need to be investigated, regardless of the circumstances. Since they go through regulatory practice and need to be safe for the public, once an accident occurs, there needs to be an investigation into who was liable, what the problem was, and what adjustments are needed from the company.

4.1 Events of Crash

A Jaguar I-PACE robotaxi in Potrero Hill, San Francisco, collided with a cyclist at the intersection of 17th Street & Mississippi Street [56]. The Waymo Robotaxi was driverless and stationary at the intersection. While Waymo was stationary at the intersection, giving way to a large commercial truck, it started proceeding into the intersection after the large truck had passed through. But shortly after, a cyclist, previously obscured behind the truck, entered the intersection and collided with the Jaguar. The Waymo robotaxi detected the cyclist and executed heavy braking, but could not avoid contact [57]. Once contact was made, the Waymo Robotaxi immediately contacted emergency services, and the police department and fire department were quick to arrive on the scene.

4.2 Waymo's Safety Systems

Waymo initially started with the Chrysler Pacifica van, which featured all the ADS systems. These Chrysler Pacifica vans were equipped with LiDARs that surround a 360-degree view, radars that can also view 360 degrees around the vehicle, and cameras that are integrated into the spinning LiDAR system on top of the car [58]. Now relevant to today, the Waymo Jaguar I-PACE is equipped with Waymo's fifth-generation self-driving system. "Waymo Driver" uses an extensive sensor suite and high-performance onboard computing to perceive the environment and plan driving actions. Each Jaguar I-PACE carries five 3D LiDAR units, six radar units, and 29 cameras positioned around the car [59]. The system uses high-definition pre-built maps of the area matched with live sensor input to localize precisely.

Waymo's software is always active and in control, which means it is always driverless and there is no human ready to intervene. In an intersection like this, the programmed behavior is to stop at the light/stop sign, yield to oncoming vehicles, and then proceed when clear. If a new obstacle appears, the system applies full braking or maneuvering to avoid a collision. In this case, once the cyclist emerged, the car's emergency braking system (EBS) engaged immediately.

Figure 11. Indicates locations of LiDAR, radars, and cameras around the Waymo Jaguar I-PACE. [60]

4.3 Consequences/Implications

4.3.1 Regulatory and Investigation Response. Local and state authorities promptly took note of the collision, and the San Francisco Police Department confirmed it was investigating the cause of the crash [61]. San Francisco's District 10 Supervisor Shamann Walton publicly reacted on social media: "So much for safety," he wrote about the Waymo crash [62]. Other city leaders and cycling advocates questioned AV readiness. For example, the San Francisco Bicycle Coalition noted that following a truck, one should assume hidden traffic [63].

At the state level, the California DMV said it was reviewing the incident [64]. Waymo itself reported contacting the relevant authorities, which presumably included both SFPD and the DMV [65]. Federally, the incident came amid broader research on AV safety. In May 2024, the NHTSA opened an investigation into Waymo's system after dozens of minor collisions with poles and barriers [66]. Although the February 6 crash itself was low-speed and minor, the event fed into concerns that even well-tested AVs can have unexpected behaviors around pedestrians and cyclists. To date, however, regulators treat Waymo's operator model as responsible for reviewing and self-reporting incidents. Waymo filed voluntary reports on other incidents, but has not disclosed a specific recall or fix for this specific cyclist collision, as it was purely unreactable by any means.

4.3.2 Financial and Operational Impact. Since this was a minor incident, no direct financial consequences specific to this crash have been reported. Waymo is a division of Alphabet (Google's parent), not a standalone public company, so its revenues are not broken out. On a broader note, Alphabet's stock was actually up in May 2025 even as Waymo issued recalls [67]. Waymo continues to invest heavily in expansion: in 2024, it advertised more than 250,000 fully autonomous passenger rides per week across multiple cities. The February 6 incident did not lead to any announced rollback of service or major cutback.

However, the crash did reinforce a cautious climate around AV operations in San Francisco. Other companies, notably GM's Cruise, faced crashes in late 2023 that led to investigations, permit suspensions, and billions in write-downs. Waymo has largely avoided such crises; this collision did not trigger new funding issues. Still, the reputational effect is notable as Waymo's trust metrics, user demand, or policy environment could be affected if multiple incidents accumulate. So far, Waymo's response to all of their minor incident has been to emphasize transparency and continual improvement [68].

4.4 Discussion

In general, nothing is threatening to public safety for Waymo to talk about. Waymo is currently the most well-known and trusted fully autonomous driver because they approach incidents and implement strategies differently. I suggest Waymo will be able to go international in the autonomous industry and possibly only have Tesla as its only rival, with Musk's new robotaxis coming in Summer 2025. Given Waymo's minor incidents and Alphabet's deep investments, it is unlikely that they will go bankrupt. Waymo's resilience comes from discipline, transparency, and not cutting corners. It has avoided the fate of many AV startups by not overhyping and not rushing. However, I am not saying that Waymo is flawless. They are consistent in handling accidents, following regulations, and using public relations means, which keeps them the most "trusted" AV company today.

5. Tesla FSD's Truthfulness

As the name implies, Full Self-Driving (FSD) leads many individuals to expect that a Tesla Model 3 or Y equipped with the latest FSD version should be capable of driving entirely autonomously, without human intervention. However, this feature is not yet available to all Tesla owners; instead, most have access to a version of Autopilot that still requires frequent human input. Even among vehicles equipped with FSD, there have been several reported incidents and safety concerns. One major incident occurred in April 2024, when a Tesla Model S operating in FSD mode struck and killed a motorcyclist in the Seattle area. Since then, Tesla has been working to improve its FSD system and enhance the way its vehicles learn and respond to real-world environments. Most recently, on June 23, 2025, Elon Musk launched the first batch of 2025 Model Y vehicles for Tesla's new robotaxi service in Austin, Texas [69]. While the initial feedback was generally positive, some users reported minor issues and driving mistakes. Many expected the robotaxis to rely on LiDAR technology commonly used by other autonomous vehicle companies, but Elon Musk took a different approach. He opted not to use LiDAR, continuing to rely solely on a vision-based system, a decision that has raised ongoing concerns about safety on public roads.

5.1 Second Crash Ever with FSD

In April 2024, a Tesla Model S equipped with FSD mode struck and killed a motorcyclist in the Seattle area. Police reported the 56-year-old driver admitted he was looking at his phone when the crash occurred [70]. The collision occurred on Friday, April 19, 2024, at about 3:45 PM Pacific time on eastbound State Route 522 [71]. The roadway was a typical suburban divided highway. No adverse weather or visibility issues were noted in the reports. State Patrol and troopers' notes say that the Tesla "lurched forward" and accelerated into the motorcycle [72]. Investigators later downloaded Tesla's Event Data Recorder (EDR). That data confirmed the car's FSD system was engaged at this time [73]. This became at least the second known fatality in which FSD was engaged. The Tesla driver was a 56-year-old man from Snohomish County [74]. The motorcyclist was Jeffrey Nissen, a 28-year-old who unfortunately passed away at the scene of the crash [74]. Nissen was riding a motorcycle on SR-522 when the Tesla, traveling behind him, collided with him from behind. Nissen was pinned under the Tesla and pronounced dead at the scene [75]. Washington State Patrol troopers arrived at the crash site on SR-522. The driver told a trooper he had FSD engaged and was looking at his cell phone when the crash happened [76]. The trooper noted the driver admitted to "inattention to driving while on Autopilot mode" and being distracted by his phone.

5.2 Tesla's FSD Safety Systems

Tesla's driver-assist systems have evolved through successive hardware versions. Since January 2023, all new Teslas have shipped with Hardware 4 (HW4), featuring upgraded cameras and a more powerful Tesla-designed FSD computer. Under HW4, Tesla fully adopted vision-only sensing, using eight high-resolution cameras to perceive the environment. The latest FSD Beta V13 software is optimized by HW4 [77]. The eight visual cameras include a significantly higher resolution, up to 5 Megapixels on the forward-facing camera, compared to about 1.2 Megapixels previously [77]. HW4 uses Tesla's second-generation FSD computer, a 7nm Samsung System on Chip (SoC) featuring multiple neural processing units, complemented by high-speed memory, over a 2 times upgrade from HW3 hardware [78]. Tesla officially eliminated radar and ultrasonic sensors by late 2022, embracing a camera-only "Tesla Vision" system. In June 2025, Tesla reintroduced a small front-facing radar-like module called "Phoenix" in new Teslas, aiming to augment perception without reverting to full radar coverage [79].

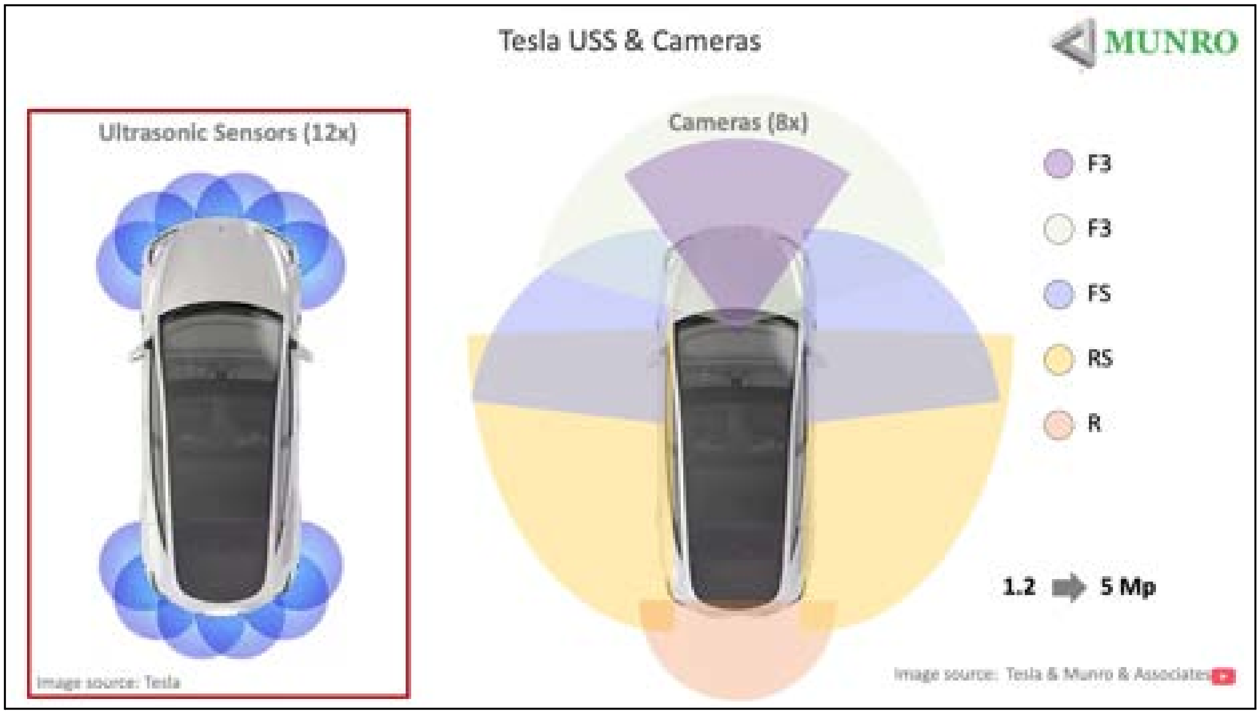

Figure 12. Tesla's Safety Systems, including its radars and cameras from an older version of Model 3. (As of 2025, Teslas being manufactured are not equipped with the ultrasonic sensors.) [80]

5.3 Regulatory & Company Impact from FSD

For the crash on April 19, 2024, the agency is examining four crashes that happened in reduced-visibility conditions, challenging Tesla's camera-based system. Consequently, NHTSA specifically asked Tesla about how FSD handles glare or fog [81]. Experts warn that camera-only autonomy can fail in glare or poor light. As of late 2024, investigations remained ongoing; regulators have noted Tesla's onboard warnings that drivers must supervise FSD, but they also question whether names like "Autopilot" invite over-reliance [82]. The string of crashes and FSD issues has drawn heavy regulatory attention. Meanwhile, the U.S. Justice Department has issued a subpoena for Tesla's Autopilot/FSD records, and Tesla has resisted public disclosure of crash data; a court filing argued that the release of hardware/software versions and crash narratives would hurt its competitive position [83].

5.4 Release of Robotaxis

Tesla began rolling out a Robotaxi ride service in Austin, Texas, with their newly manufactured 2025 Model Y in June 2025. The limited robotaxis used about 10 Model Y vehicles to provide paid demo rides within a geo-fenced area [84]. Only a select group of individuals and influencers were hand-picked to ride in the robotaxis around Austin. A handful of feedback were issued by the multiple influencers who were recording and vlogging whilst riding the robotaxis. Instead of a smooth debut, social media videos by Tesla fans captured several troubling glitches. In one clip, a Robotaxi misjudged a turn, drifted into the oncoming lane for about ten seconds, then swerved back [84]. Another showed a car exceeding the posted speed limit by several miles per hour. A different video appeared to show a Robotaxi braking abruptly mid-block, possibly from responding harshly to flashing police lights [85]. These erratic behaviors prompted NHTSA to request information and investigate the incidents. Tesla CEO Musk proclaimed the rollout a big success, and Wall Street's Wedbush analyst, Dan Ives, downplayed the missteps as inevitable growing pains, noting that such issues will be 'fixed' over time [85]. So far, no injuries have been reported in the Robotaxis, but further testing will underscore the gap between Tesla's vision and the current reality.

Figure 13. Picture of a 2025 Model Y Robotaxi caught in Austin, Texas. [85]

5.5 Who Takes the Blame?

A significant number of accidents involving self-driving Teslas occur, making it unclear who would be held responsible for one of these incidents. Under current U.S. law, all drivers are liable for the operation of their cars. NHTSA states that today's systems of Autopilot/FSD require the driver to stay alert and keep hands on the wheel when prompted [82]. Tesla's documentation and in-car alerts explicitly tell drivers to supervise Autopilot [86]. However, critics argue that names like "Autopilot" or "Full-Self Driving" inherently imply that the car can drive by itself, which may lead users to overtrust the system [87]. NHTSA itself has noted that calling a system "Autopilot" elicits the idea of drivers not being in control and can invite drivers to overly trust the automation, therefore making the driver believe they will not be entirely at fault in the event of an accident [87].

In civil trials, victims' lawyers often characterize a crash as a product defect or negligent design. Tesla's defense so far is to blame driver negligence and to say its features worked as intended. For example, in one case, Tesla pointed to the driver's intoxication [87]. To date, juries have usually found against defect claims. In the 2023 Riverside trial, the 12-member jury rejected the plaintiffs' defect theory, and Tesla won earlier suits by stressing that its warnings were obvious enough [88]. Internal documents revealed at trial prompted Tesla to update its software, but legally, Tesla has not been found strictly liable yet. Still, the legal waters are shifting; a Florida judge's recent ruling implied Tesla knew about performance flaws, and some victims' families are pursuing multi-million-dollar suits [88]. Since there are no federal rules that allocate liability differently for semiautonomous cars, drivers remain on the hook [82]. Policymakers acknowledge this is a growing issue, as NHTSA notes that as autonomy increases, questions of liability and insurance are among many important questions that are at work to be addressed.

Discussion

The regulatory field surrounding the AVs in the United States remains fragmented and uneven, contributing to both progress and challenges in AV deployment. Despite the ethical dramas, unsolved liability issues, and difficulty of keeping pace with the evolving technologies, there still seems to be some federal hesitation on whether to establish a comprehensive national framework. Without federal involvement in AV policies, the burden of liabilities and regulations falls on individual states, exposing vulnerabilities in AV policy development. At the federal level, regulators such as the NHTSA have prioritized observation and limited intervention, only issuing voluntary guidelines rather than enforceable standards. In the absence of enforceable standards from the NHTSA, the risk of technological and ethical failures increases, as seen in the 2018 Uber crash, where reasoning was a contributing factor. Moving down, states such as Arizona, California, Nevada, Florida, and Texas have taken widely varied stances on AVs. These states have become the main testing grounds for the AV industry today due to their lenient regulatory environments and strong tech ecosystems. For example, states like Arizona allow for more aggressive testing with minimal oversight. In contrast, states like New York or Connecticut have imposed restrictions on any sort of AV testing and bans on AV deployment due to concerns over safety and liability ambiguity. Reasons why certain states like New York and Connecticut could be from many of the high-profile AV incidents analyzed in this paper, which can be traced to inadequate regulatory frameworks. The lack of mandatory driver training protocols, real-time monitoring standards, or minimum system redundancy requirements enabled companies to prioritize speed of development over safety. The permissive policies in Arizona facilitated rapid rollout in AV development, which led to the failure of safeguarding human oversight and flawed object detection systems.

Ethical dilemmas continue to challenge policymakers: Should AVs be programmed and trained to prioritize passenger safety over the safety of a pedestrian? Who is liable when a vehicle operating under imperfect AI crashes? These issues, combined with technological limitations such as faulty sensor fusion, the inability to recognize uncommon obstacles, and weather-based performance variability, highlight the pressing need for deeper regulatory engagement. Moreover, the current regulatory frameworks do little to address algorithmic transparency or data privacy, which are both critical when AVs rely only on real-time data sharing and decision-making. Currently, frameworks also lag in requiring sufficient cybersecurity protections to prevent any sort of tampering or hacking. For a more robust AV future, federal regulators should establish a comprehensive, enforceable standard for AV safety testing, operator training, and public road deployment. Examples of such policy improvements could include mandatory third-party safety validation before deploying any AV systems, the requirement to report all AV-involved incidents, and the implementation of ethical programming guidelines to prevent further ethical dilemmas. Concluding federal policy on this, the overall views of the most relevant autonomous industries requiring/required these framework changes comes down to: Waymo, Cruise, Zoox, and Tesla. With the current frameworks in place as of 2025, Figure 14 illustrates how these companies present their testing data, implement safety protocols, and manage their autonomy.

AUTONOMOUS VEHICLE COMPANY COMPARISON

COMPANY	SENSOR CONFIG	SOFTWARE ARCHITECTURE	SAFETY	TESTING & DATA COLLECTION
WAYMO	13 cameras, LiDAR, radar, audio sensors providing overlapping 360 degree coverage	Uses layered architecture; prediction and planning; heavy simulation testing	Best-level safety system, prioritizing redundancy, publishes crashes & safety data per incident.	Simulation-based CAT* millions of on-road and virtual test miles.
cruise	LiDAR, radar, and cameras integrated into purpose-built vehicles	Proprietary AI stacks for city driving, high-resolution mapping integrated by General Motors.	Redundant sensor layers; safety overseen by CA DMV, post-crash investigations strengthened internal protocols.	Extensive public road testing in SF, Phoenix, and Austin, followed by permits revoked and operations passing in 2023.
ZOOX	4 LiDARs redundant radar & camera suite; bespoke shuttle-style EV with symmetrical sensor arrays for all-around perception.	End-to-end neural-nets* with heavy use of virtual simulations; vehicle supported full autonomy without manual controls.	Safety via redundancy and constant updates, voluntarily recalled vehicles after San Francisco e-bike incident.	California and Nevada public road testing, recalls triggered by NHTSA, integration of extensive test suite and scenario databases.
TESLA	Vision-only; 8 external cameras, removed radar and ultrasonic in 2022; only relies exclusively on neural net* inference from camera data.	End-to-end neural net* trained on billions of supervised miles with driver oversight; AI trained through multiple black-box clips.	Relies on massive scale data ingestion; less redundancy, criticized for safety transparency issues and limited external oversight.	Testing through customer-use miles; FSD beta deployed to hundreds of thousands in order to train model; minimal simulation outside telemetry*.

Figure 14. Table summarizing 4 relevant autonomous industries: Waymo, Cruise, Zoox, and Tesla, including ADS technology, safety briefings, testing data collection methods, and software structure. [89] [90] [91] [92] [93] [94]

1. Neural Network* : A computer system modeled on the human brain and nervous system.

2. CAT* : Collision Avoidance Testing.

3. Telemetry* : Different types of sensors installed on a vehicle to obtain data of: speed, location, acceleration, and fuel consumption.

Conclusion

The evolution of autonomous vehicles in today's world has been marked by the rapid development of the autonomous companies that I have covered in this paper. From the early optimism fueled by billions in investments from companies like Google, General Motors, and SoftBank, to the unexpected outcomes of high-profile accidents involving Uber, Cruise, Zoox, Waymo, and Tesla, the trajectory of AVs has been anything but linear. Case studies such as Uber's 2018 fatal crash in Arizona, Cruise's pedestrian-dragging incident in San Francisco, Zoox's collision with a scooter in San Francisco, and Tesla's FSD-involved motorcycle crash show the immense complexity between the technological promises and real-world consequences. These incidents exposed the gaps in government regulations, challenges with liability, and the limitations that hold back the advancements of autonomous vehicles.

Through this research, it has become clear that the environments in which AVs are tested and deployed are influential in both performance and public reaction. The lack of consistency in regulation across jurisdictions has created fragmented oversight, contributing to uncertainty in safety standards and accountability. Additionally, technological choices, such as Tesla's decision to rely solely on cameras instead of LiDARs, raise important questions about trade-offs between cost, safety, and reliability. Furthermore, the use of cameras also raises concerns about various complexities, real-time accuracy in obstacle detection, and data processing.

Despite various setbacks, AV technology continues to develop. Companies are refining their sensor suites, updating AI decision-making algorithms, and expanding simulation-based testing environments to improve safety. Still, the industry must balance innovation with responsibility and time. Transparent communication with the public, robust third-party safety validation, and a clear regulatory framework will be the answers to a successful autonomous future. The key takeaways of this research are that the future of autonomous transportation depends not only on technical achievement but also on how well developers manage risk, ensure accountability, and prioritize public trust. These lessons are not merely about machines: they are about the systems we build around them and the lives that they affect. As this AV technology advances through our roads, cities, and policies, the safety of human transportation must remain at the forefront. Only then can AVs fulfill their priorities of reducing traffic, improving mobility, and redefining how the world will move on.

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