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Autonomous Vehicles andVulnerable Road User Safety

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Autonomous Vehicles and Vulnerable Road User Safety

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Abstract

As autonomous vehicles (AVs) become more prevalent on roads in the United States, relevant information on their safety, especially when interacting with vulnerable road users (VRUs) like bicyclists and pedestrians is crucial. To understand the current state of AVs, this brief reviews VRU perceptions and interactions with AVs, relevant crash data on AVs, the use of AVs as a ride-hailing service, and AV technology and design. This brief examines technology, infrastructure, and data trends that can help inform communities on how to safely walk and bike amongst AVs. Knowledge of these topics may also help inform the public about AV safety, help AV manufacturers address technical concerns, and aid policymakers in developing legislation.

Introduction

AVs are becoming increasingly integrated within California's transportation fleet, especially in major cities like San Francisco and Los Angeles. While AVs may bring benefits like a reduction in human driving error, many road users have concerns about their unpredictability and unfamiliarity. In 2025, UC Berkeley Safe Transportation Research and Education Center (SafeTREC) surveyed residents of San Francisco, who have more exposure to AVs than other US demographics, and found 29.6% of residents are unsure about the safety of AVs while 8.6% are fearful.[1] In comparison, data from the national 2019 American Automobile Association (AAA) survey revealed larger distrust levels across the nation, with 71% expressing extreme or large concern about technology malfunction in AVs.[2] This discrepancy indicates a need for increased awareness and exposure to education on AVs, as they continue to expand across the US.

The 2025 survey also found that pedestrians and bicyclists are less likely to trust the safety of AVs than AV passengers,[1] with trust levels of 51.0% and 72.5% respectively. This shows about half of those walking and biking in San Francisco do not trust the safety of AVs. These findings demonstrate a need for more comprehensive literature and education on the safety of those walking and biking on roads alongside AVs to help the general public achieve a better understanding of the real risks, rather than their perceived safety or danger. This brief aims to provide an overview of all factors relating to AV and VRU safety and serve as a resource for AV manufacturers and policymakers. Within this brief, we define VRUs as pedestrians, bicyclists, motorcyclists, and e-bicyclists, and AVs as driverless autonomous vehicles.

Vulnerable Road User Perceptions and Interactions with Autonomous Vehicles

Perceptions

Across studies, VRUs have varying perceptions of AVs and their safety. Positive perceptions of AVs include their greater adherence to traffic rules, that they are safer than human drivers, and that more space is provided between the AV and a VRU than with human drivers.[3] Negative perceptions of AVs include VRU concerns about perceived safety and comfort, and driving patterns.[3] However, research indicates negative perceptions towards AVs are highly influenced by one's knowledge and familiarity with them,[3] and increased exposure to AVs is likely to increase positive perceptions of them.[4–7] These findings align with findings from UC Berkeley SafeTREC and the AAA, where participants' exposure to AVs greatly impacted their perceptions.

In recent years, the approval, safety, and comfort of AVs for VRUs was also studied. Asadi-Shekari et al.[8] determined that VRUs' approval of having AVs on public streets depends on their impact on traffic injuries and fatalities, and their maximum speed. According to Guirado et al.,[9] VRUs (63%) also express more concern about system malfunction in AVs than passengers (45%) in the AVs. For bicyclists, numerous studies concluded that those biking feel more safe and comfortable sharing the road with AVs when there is street infrastructure providing separation between them, like striped bicycle lanes and protected bicycle lanes which provide physical barriers.

Interactions

Interactions with AVs that significantly affect VRU perceptions of comfort and safety include yielding, lack of eye contact, and distance from them. Multiple studies discuss how AVs yielding behavior plays a role in perception of safety.[10] However, research indicates that finding a balance between programming for excess and insufficient yielding in AV algorithms is crucial. Otherwise, pedestrians may always expect AVs to yield at crosswalks without watching for signs of yielding (i.e. decrease in speed, gauging distance), which may compromise their safety. Signaling of yielding and yielding intent through External Human-Machine Interfaces (eHMIs), which we discuss below can improve interactions between VRUs,[11] especially bicyclists.

VRUs often report loss of eye contact as a point of discomfort when interacting with AVs. SafeTREC's 2025 survey determined that approximately 53.5% of VRUs in San Francisco feel lack of eye contact affects their comfort.[1] A study by Gaio and Cugurullo found loss of eye contact as the most frequent topic of concern when discussing AVs.[13] Pedestrians also report loss of eye contact as a point of discomfort, as shown in a study by Gao et al. where they frequently voiced their desire for eye contact.[12]

Distance is another factor in VRU and AV interactions. Madigan et al.[14] analyzed video footage from AVs, which showed that VRUs tend to maximize their buffer distance from AVs. Establishing common factors in interactions will further research and technological advancements may facilitate smoother traffic flow between road users and reduce severe injuries and fatalities.

Figure 1: Autonomous vehicle double parked during passenger pickup on a commercial corridor.24

Autonomous Vehicle Design for Vulnerable Road User Safety

AVs have technological features that allow them to effectively maneuver around and interact with VRUs. These include communication and braking mechanisms.

Communication Mechanisms

External human-machine interfaces (eHMIs) are essential to positive perceptions of AVs by VRUs,[26] as well as positive interactions between the two. eHMIs on AVs communicate the vehicle's intent via light-up signals or audio cues, replacing the communication normally conveyed by human drivers through eye-contact, nods, hand waving, and other gestures. Multiple studies have discussed the importance of both visual and audio cues for VRU perceptions of safety and comfort[27,28] and eHMIs aim to provide these cues for the AV.

The use of eHMIs as seen in Figure 2 is important in interactions with pedestrians. In a crosswalk scenario, one study found eHMIs significantly increase pedestrians' confidence in the AV to yield when paired with gentle braking.[31] However, when pedestrians are deciding to cross the street, perception and evaluation of speed and distance were found to be even more important than the presence of eHMIs.[28]

The use of eHMIs is even more critical for bicyclists who frequently navigate dynamic, mixed-traffic environments at much higher speeds than pedestrians. Because bicyclists often need to make split second trajectory decisions while sharing a travel lane with vehicles, clear AV communication is vital. Studies found text-based eHMIs,29 contrasting colors, animations, and placement on large surfaces of the vehicle11 were the most effective for bicyclists. One paper also emphasized the importance of developing distinct signals to reduce confusion between pre-existing vehicle signals.11 Demographically, research determined that older bicyclists demonstrate less comprehension and responsiveness to eHMIs compared to younger ones.[30] Similar results were observed with bicyclists with lower education levels compared to those with advanced degrees. These findings suggest a need to design eHMI signals that are intuitive and accessible to older adults, individuals with varying educational backgrounds, and as multilingual communities.

Figure 2: eHMI on an autonomous vehicle displaying a pedestrian walking sign. [25]

Braking Mechanisms

Braking is one of the most significant considerations for VRU safety and risk of injury. Research on automatic emergency braking systems (AEBs) in AVs determined that they reduced VRU crash risk on high speed roads and crash frequency at intersections.[32] Another study determined that at speed zones greater than 50 km/hr, autonomous vehicles with AEBs, compared to those without, reduced risk of permanent medical impairment by 44% for pedestrians and 35% for bicyclists.[33]

However, some literature suggests that AV manufacturers prefer a more conservative approach with braking mechanisms, which may increase the occurrence of sudden, unexpected braking events (phantom braking).[34] Witnessing phantom braking may affect VRU trust and perceptions of AVs, especially due to the unpredictability of the event and future events.

Crashes between Vulnerable Road Users and Autonomous Vehicles

Research on crash frequency and the likelihood of crashes between VRUs and AVs is currently conflicting. A data study utilizing time-to-collision analysis suggests that 28% to 73% of fatal crashes involving manually driven vehicle crashes and pedestrians could have been avoidable, if the manually driven vehicle was replaced by an AV.[15] One simulation study found increasing the numbers of AVs on the road reduced pedestrian conflicts at roundabouts with slip lanes.[16] However, another simulation study observed that the implementation of AVs reduced the perceived level of stress but did not improve bicyclist safety.[17]

AVs operating in the transportation fleet may reduce instances of human error, such as being distracted, sleep deprivation, or driving under the influence. However, there are also areas AVs may perform worse in than humans, like decision-making, evaluating road conditions, and technological malfunctions. Therefore, current studies in the field are inconclusive on whether AVs are able to improve VRU safety and further research is necessary to evaluate these effects.

Crash data is also relevant to understanding common variables in crashes between VRUs and AVs. Data from the National Highway Traffic Safety Administration (NHTSA) and the California Department of Motor Vehicles (DMV) is synthesized in the following sections. These two datasets measure different variables due to different reporting requirements between the California DMV and NHTSA, but may provide insights to understand the safety of AVs.

California Department of Motor Vehicles Data

The California DMV requires all AV manufacturers to report testing crashes. Testing refers to the operation of AVs on public roads for research and development. Testing vehicles often have human operators to help manage or intervene with the AV, in case of an emergency.

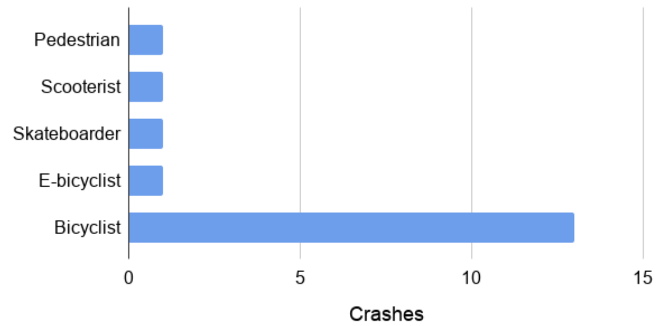

Figure 3: AV crashes by vulnerable road user involved, 2023 – March 2026. Source: California DMV.

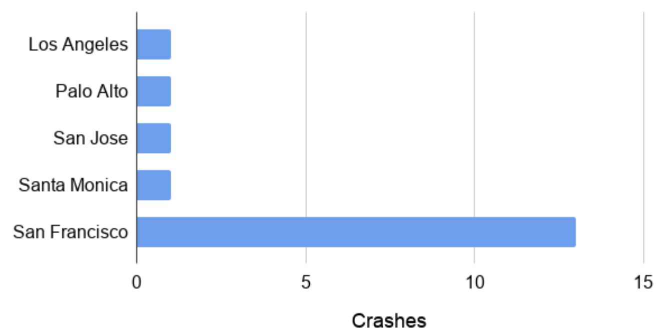

Figure 4: AV crashes involving vulnerable road users by city, March 2023 - 2026. Source: California DMV.

The California DMV reported 17 total crashes between VRUs and AVs,[20] between 2023 and March 2026. The majority of crashes, 76.5%, involved bicyclists as seen in Figure 3. Additionally, 76.5% of all crashes occurred in San Francisco alone as seen in Figure 4. The following is a brief descriptive summary of two of the crashes:

- A bicyclist appeared to dismount their bicycle, then the bicyclist made contact with the front passenger side of the AV; the bicyclist received medical attention and was transported to a hospital.
- A bicyclist crossed into traffic in front of an AV, made contact with the front bumper, then the hood of the stationary AV; the

bicyclist was transported to a hospital, injuries reported were loss of consciousness and complaint of pain.

Additionally, research evaluating California DMV data[18] determined the most likely crash location between an AV and a VRU is midblock in business areas, with little traffic control and marked crosswalks.

National Highway Traffic Safety Administration Data

The following data comes from the Standing General Order (SGO) that the NHTSA issued in 2021,19 which requires all AV manufacturers to report testing and deployment collisions. Deployment is the stage where AVs are commercially available to the public for ride-hailing services.

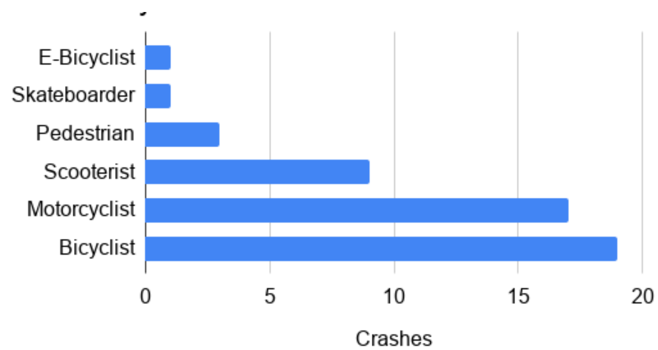

Figure 5: AV crashes by vulnerable road user involved, June 2024 - April 2026. Source: NHTSA SGO data.

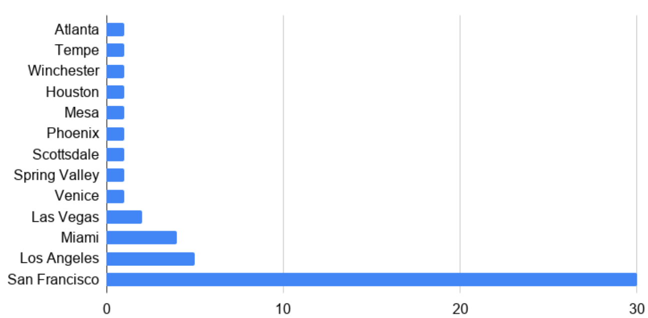

Figure 6: AV crashes involving vulnerable road users by city, June 2024 - April 2026. Source: NHTSA SGO data.

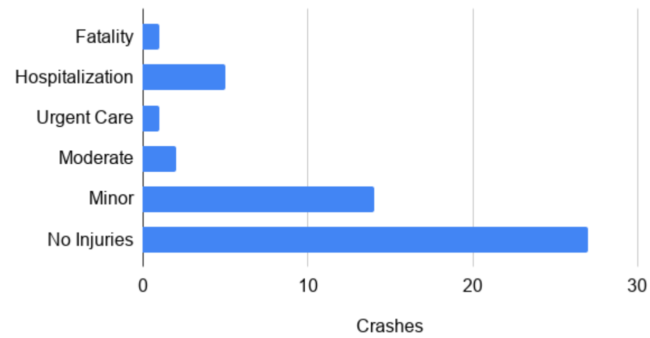

Figure 7: AV crashes involving vulnerable road users by injury severity, June 2024 - April 2026. Source: NHTSA SGO data.

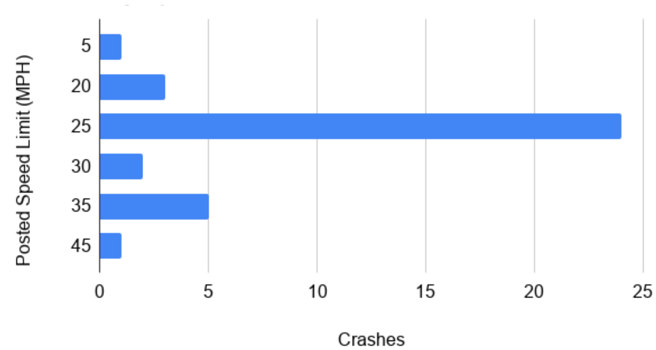

Figure 8: AV crashes involving vulnerable road users by posted speed limit, June 2025 - April 2026. Source: NHTSA SGO data.

The SGO reported 50 crashes between vulnerable road users and AVs, between June 2024 and April 2026 as seen in Figure 5 through Figure 8. Of these crashes, 72% occurred in California, 8% occurred in Arizona, and 4% occurred in Nevada. Notably, 60% of all crashes occurred in San Francisco alone. VRUs represented most in these crashes were bicyclists at 38%, motorcyclists at 34%, and scooterists at 18%. Fourteen of the 50 total crashes resulted in a minor injury, five in hospitalization, and one person was killed. For crashes after June 16, 2025, over two-thirds (64.9%) occurred within a 25 mph speed limit zone, and 13.5% occurred within a 35 mph speed limit zone.

The following is a brief descriptive summary of two crashes:

- A motorcyclist rear-ended an AV, then the motorcyclist fell and was struck by a car. The motorcyclist was transported to the hospital and declared deceased.
- An AV was parked in-lane for passenger drop off. When the passenger opened the vehicle door, it hit a bicyclist; the bicyclist reported minor injuries.

Autonomous Vehicles as a Ride-Hailing Service

At the time of this brief's publication, the majority of all AV transportation fleets operate as ride-hailing vehicles. This helps inform safety considerations, especially in the context of VRUs. As AVs are optimized for passenger pick-up and drop-off, this can lead to parking in bike lanes or double-parking. Consequently, passengers exiting the AV may risk obstructing bicyclists or other motorists in the bike lane or blocked vehicle lane. News outlets have covered cases where AVs were parked in the bike lane which lead to a crash with a VRU.[21,22] One such case involved an AV passenger dooring a bicyclist in the bike lane, resulting in serious injuries to the bicyclist. The California Public Utilities Commission is also reporting such incidents; in 2024 the agency required further AV data reporting of citations and stoppage events.[23]

Safety considerations are key for improving the safety of VRUs in cities with AVs, including education to allow road users a way to understand the changing transportation landscape and how it affects them. Awareness of AV operational status is also important for AV companies to balance both commercial and safety interests, and for policymakers to develop targeted and effective policies.

Discussion

While the literature review and data discussed is a helpful starting point, there are multiple factors to consider when informing the public about AV safety, addressing technical concerns with AVs, and developing legislative changes. The NHTSA and California DMV data is sourced from crash reports written and submitted by AV manufacturers, not government agencies. This data, while informative, must be viewed through the lens of potential manufacturer bias and competing interest implications. Furthermore, the reliance on international studies introduces variables that may not be directly relevant to the US. This is important to consider, given the unique characteristics of the US AV transportation fleet, transportation laws, and infrastructure compared to other countries.

Moving beyond research limitations, the deployment of AVs nationwide faces complex operational hurdles. As AV technology continues to mature, geographical considerations and regulatory limitations may become important. For example, if an AV needs to travel across state or even across country boundaries, manufacturers may need to integrate different municipalities' transportation laws and infrastructure into the vehicle's algorithm.[35] This might be a significant challenge, given the diversity of transportation regulations and customs across municipalities. AVs may also need to be calibrated to better operate under challenging weather conditions, such as low-visibility situations like heavy fog or snow.

Despite these operational complexities, a larger expansion of AVs into the transportation fleet may bring potential benefits. If deployed effectively, AV technology could reduce human driving error and vastly increase mobility access to transportation for riders with disabilities. Ride-hailing AVs also have the potential to reduce urban congestion and the spatial demand for parking in city centers.

Conclusion

Various factors shape the complex dynamics between AVs and VRUs on the road. While current perceptions and interactions provide perspective on VRU opinions, the evolving market and emerging technology demonstrate how AV developers are actively approaching VRU safety. As AVs inevitably expand into more US cities and states and transition away from fleet testing to personal ownership, a two-pronged approach is needed. Considerations include targeted community education to demystify AV technology, as well as research on best technological advancements for VRU safety.

Ultimately these findings suggest that AV deployment is complex and encompasses technical technological advancements, alongside regulatory and social challenges. While this brief focuses on the critical need to understand VRU perception of AVs, future research must expand to address real world behavioral dynamics, physical conflict points, and the non-verbal communication systems needed to coexist in a shared space. By combining insights from both subjective perceptions and objective physical interactions, policy makers and AV companies can move beyond current limitations to design a transportation system that is even safer for all road users.

About the Program

This research brief was developed as part of the Community Pedestrian and Bicycle Safety Program (CPBSP). The aim of the CPBSP is to reduce pedestrian and bicyclist fatalities and serious injuries in California. We partner with communities across California to discuss, plan, and implement safety improvements and projects. The CPBSP prioritizes working in communities that are at disproportionate risk for road traffic injuries and addressing the safety needs of people who are underserved by traditional transportation resources and planning.

For more information, visit https://bit.ly/CPBSP or email us at safetrec@berkeley.edu.

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