

Descriptive analysis of reports on autonomous vehicle collisions in California: January 2021–June 2022

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Abstract: The characteristics of autonomous vehicles' collisions from 2021 and the first half of 2022 in California confirm trends reported in previous years. Driving in autonomous mode was associated with fewer instances in which the AV was deemed to be at fault in a collision. Most collisions in autonomous mode were rear-end collisions at intersections. Single vehicle collisions occurred mostly in manual mode. Collisions with vulnerable road users occurred mostly while the autonomous vehicle was in manual mode, often right after disengagement from autonomous mode. In collisions with other vehicles that occurred after disengagement, the other vehicles were frequently deemed to be at fault. Compared to 2021, the collision reports from the first half of 2022 indicate higher shares of collisions in autonomous mode, rear-end collisions, and collisions with vulnerable road users.

Keywords: autonomous vehicles, collisions, disengagements, safety

1 Introduction

A part of the EU's executive plans is to propose by the end of 2022 the world's first technical legislation that will allow member states to approve the registration and sales of limited numbers of vehicles with advanced, SAE level 4, self-driving technology (Posaner 2022). As safety is a major concern in deploying such autonomous vehicles (AVs) into complex traffic environment, knowledge and learning from reported AVs collisions are essential.

Currently the most comprehensive data on AVs collisions have been gathered by the Department of Motor Vehicles (DMV) in California, US. Since 2014, DMV has administered the Autonomous Vehicles Program and issues permits to companies that test and deploy AVs on California public roads. AVs tested in California are typically passenger cars, mostly operating under 'conditional driving automation', i.e. SAE level 3 and recently level 4 (SAE 2021). The program requires all collisions ('any collision that resulted in property damage, bodily injury, or death within 10 days of the incident') and disengagements ('disengagements from autonomous mode because of technology failure or situations requiring the test driver/operator to take manual control of the vehicle to operate safely') to be reported to the DMV. As of August 23, 2022, the DMV has received 506 Autonomous Vehicle Collision Reports (DMV 2022). The

collected data are publicly available from an online database. This database has frequently been harvested by researchers to explore various aspects of AVs' collisions. Results from previous studies show consistently that AV collisions typically are of relatively low severity and are often rear-end collisions (see Table 1 for an overview).

Table 1 Overview of DMV studies

Study Sample size Studied period	Key findings (related to collisions and disengagements)
Dixit <i>et al.</i> (2016) 12 collisions 9/2014–11/2015	No serious injuries reported. All collisions were either rear-end or side-swipe. System failure was the most common cause of disengagement.
Favarò <i>et al.</i> (2017) 26 collisions 9/2014–3/2017	Rear-end collisions were the most frequent collisions type. In 85% of collisions, AV was not-at-fault.
Biever <i>et al.</i> (2019) 115 collisions 9/2014–6/2019	Rear-end collisions (AV being struck) most frequent (59%). 30% of collisions were side impacts (AV being struck). 9% of collisions related to disengagement. 92% of collisions in very low speed, 14% of collisions resulted in an injury (mostly minor).
Leilabadi & Schmidt (2019) 138 collisions 9/2014–3/2019	Rear-end collisions (AV being struck) most frequent Most of the collisions result in minor damages. 12% of collisions related to disengagement
Wang & Li (2019) 113 collisions* 2017–2018	In collisions with AV in automated mode, non-AV's is more likely to be at-fault. Rear-end collisions (AV being struck) most frequent, followed by being sideswiped. More severe injuries on the highway.
Xu <i>et al.</i> (2019) 72 collisions 1/2015–6/2018	Rear-end and sideswipe collisions were predominant collision types. Stopped AV and conventional car proceeding straight is the common pre-collision scenario. The severity of AV collisions is lower than in collisions with conventional cars.
Ye <i>et al.</i> (2020) 133 collisions 1/2017–6/2019	71% of the injured were AV occupants (head and neck were the most commonly injured). Driving in poor lighting was associated with greater injury risk. Collisions with VRU or incidents happening during commute periods led to more injuries.
Alambeigi <i>et al.</i> (2020) 167 collisions 10/2014–6/2019	30% of collisions associated with disengagements were sideswipes during overtaking.
Boggs <i>et al.</i> (2020a) 153 840 disengagements 10/2014–11/2018	Human-initiated disengagements are more likely than ADS initiated disengagements. ADS-initiated disengagements are mostly due to planning and hardware/software discrepancies and occur on streets and roads environments than on high-speed facilities.
Boggs <i>et al.</i> (2020b) 124 collisions 10/2014–11/2018	61% of collisions were rear-end collisions, with higher likelihood in mixed land-use settings. 13% of collisions were injury collisions. 10% of collisions were related to disengagement. Injury collisions are less likely at roadways with marked centrelines and in clear weather.
Das <i>et al.</i> (2020) 151 collisions 9/2014–5/2019	Current narrative documentation is not sufficient in determining the driving mode. Classes associated with turning, multi-vehicle collisions, dark lighting conditions with streetlights, and sideswipe and rear-end collisions were associated with a higher proportion of injury severity level.

Table 1 *cont.*

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Das et al. (2020) 151 collisions 9/2014–5/2019	Current narrative documentation is not sufficient in determining the driving mode. Classes associated with turning, multi-vehicle collisions, dark lighting conditions with streetlights, and sideswipe and rear-end collisions were associated with a higher proportion of injury severity level.
Petrović et al. (2020) 53 collisions 2015–2017	64% of AV collisions were rear-end collisions (vs. 28% for conventional car crashes). Collision types ‘broadside’ and ‘pedestrian’ represented a total of 5.7% of AV collisions, while 42% of conventional car collisions.
Goodall (2021) 256 crashes 10/2014–3/2020	AV in autonomous mode were struck from behind at 4.8 times the rate of conventional car in a naturalistic driving study. AVs were more likely to be struck when stopped than when moving compared to conventional cars.
Chen et al. (2021) 131 collisions 1/2019–10/2020	The most of rear-end collisions are conventional vehicles bumping into the rear of AVs. Weather and low-visibility conditions increase the probability and seriousness of collisions.
Kutela et al. (2022) 35 collisions 2017–2020	Bicyclists and scooterists are more likely to be involved in the AV collisions directly, and bicyclists are likely to be at fault. Pedestrians appear more in the indirectly involvements. collisions that involve VRUs indirectly are likely to occur when the AVs are in autonomous mode. Crosswalks, intersections, traffic signals, movements of AVs are the key predictors of the VRUs-AV related collisions.

* This study included also six AV collisions outside California that were reported by the National Transportation Safety Board (NTSB). In the table we include only the findings relevant to collisions from DMV database.

Because of the rapid development in AV technology and other factors such as increased walking and cycling in urban areas, new patterns might emerge in AV collisions. Therefore, in our study we utilized the DMV database to explore whether recent collision data (i.e. collisions reported in 2021 and in the first half of 2022) provide any evidence for changes. Additionally, we compared characteristics of collisions where the AV was in manual mode, autonomous mode, or right after disengagement.

2 Method

2.1 Descriptives

This study utilizes DMV collisions reports from period January 2021 to June 2022. Using descriptive statistics, it explores the following variables from the DMV database:

- Collision type and location
- Type of road user(s) involved
- Severity levels
- AV mode in collision (manual, autonomous, after disengagement)
- Road user at-fault (estimated from collision narratives)
- Million vehicle·kilometres travelled (MVKT)—available only for 2021.

2.2 Odds ratios

For comparing shares of collision properties between types of collisions we calculated odds ratios with 95% confidence intervals according to [Christensen \(1990\)](#).

3 Findings

3.1 Time periods

In 2021, eight companies reported 117 collisions to the DMV. The total distance driven by these eight companies was 6.06 MVKT (0.02–3.74 range). These were the highest annual values reported to the DMV database so far, both for collisions and distance travelled. In the first half of 2022, the testing companies reported 91 collisions to DMV. No data on MVKT is available for 2022.

3.2 Mean collision rate

The mean collision rate of AVs in 2021 was 19.3 collisions per MVKT, which is very similar to earlier studies. The smaller companies (1–9 reported collisions) had a higher mean collision rate (24.6 per MVKT) than the two largest companies that together account for 85% of MVKT (30 and 64 collisions, 18.2 collisions per MVKT).

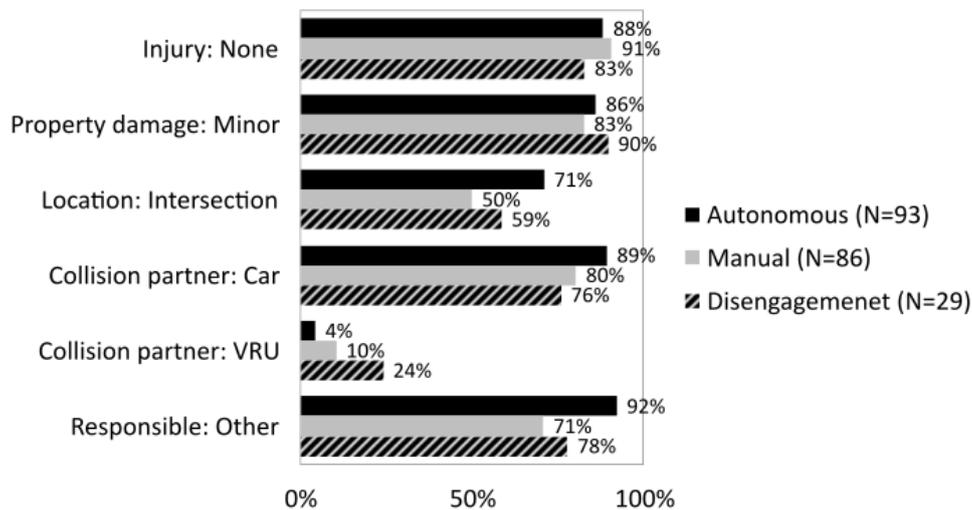


Figure 1 Collision characteristics by AV mode: VRUs include bicycles, pedestrians, e-scooters, and motorcycles; cars include passenger cars, vans, SUVs and pick-ups

Table 2 Comparison of collisions’ characteristics between 2021 and first half of 2022

		2021–2022 (n = 208)	2021 (n = 117)	2022 (n = 91)
Mode:	Autonomous	45%	38%	53%
	Manual	41%	43%	40%
	After disengagement	14%	19%	8%
Collision type:	Rear-end	45%	40%	52%
	Sideswipe	23%	25%	21%
Injury:	None	88%	85%	93%
Property damage:	Minor/none	85%	86%	84%
Location:	Intersection	61%	65%	55%
Collision partner:	Car	84%	85%	81%
	VRU	10%	7%	13%
Responsible:	Other	81%	79%	85%

Figure 1 shows collision types and other collision characteristics by AV mode for the whole studied period, while Table 2 compares selected characteristics of AV collisions between 2021 and the first half of 2022.

3.3 Primarily autonomous mode

In most collisions, the AV was in autonomous mode (93 collisions, 45%), followed by manual mode (86 collisions, 41%). The remaining 29 collisions (14%) occurred right after a disengagement. The share of collisions in autonomous mode increased from 38% to 53% from 2021 to 2022, the share of disengagement collisions decreased from 19% to 8%, while the share in manual mode was about unchanged (decreased from 43% to 40%).

3.4 Odds for being at-fault

When in autonomous mode, the odds of being at-fault was reduced by 78% compared to other modes (95%, CI¹ [-91%; -46%]). Since being at-fault was assessed based on AV-company reports, there may be some bias in the assigned responsibility in favour of AVs.

3.5 Severity levels

Most collisions involved no injury (88%) and only minor or no property damage (85%), without a substantial difference between modes and years. From 24 injury collisions, 22 (92%) involved minor injuries; the remaining two collisions resulted in a moderate injury.

Most (n = 16; 67%) injury collisions involved a car. AV was in an autonomous mode in 56% of these collisions. Most injury collisions with cars were rear-end collisions on intersections when the AV stopped prior to the collision and then was hit by another car.

VRU (mostly cyclists) were involved in eight injury collisions (33%). AV was in motion in all these collisions, and in all but one AV was after a disengagement or in automated mode. There was no obvious prevailing type of collision with VRU.

3.6 Collision locations

Most collisions occurred at intersections, both in 2021 and 2022. In autonomous mode the odds of a collision occurring at an intersection are far higher than of occurring at other locations (124%, CI [26%; 300%]).

3.7 Collision types

Figure 2 shows that most collisions were rear-end collisions, followed by sideswipes. When all modes are regarded together, the share of rear-end collisions increased from 40% in 2021 to 52% in 2022 (45% in total). However, the share of rear end collisions in autonomous mode was about unchanged (62% in 2021 vs. 69% in 2022).

Rear-end collisions in autonomous mode are occurred typically at intersections where another vehicle was rear-ending the AV. Such collisions occur often because the AV brakes abruptly as the traffic signal switches to yellow, while following drivers expect it to continue until the light switches to red (Biever *et al.* 2019). In autonomous mode the odds of a collision being a rear-end collision is far higher than otherwise (374%, CI [163%; 753%]).

Sideswipes occurred equally often at intersections and mid-blocks. Besides single vehicle collisions, sideswipes are also the collision type where AVs were most often at-fault (20% of all sideswipes vs. 6% of rear-end collision). Remarkably, in most sideswipe collisions in which

¹ 95% confidence interval (CI)

the AV was deemed to be at-fault (six out of nine collisions), the AV was in manual mode and hit a parked vehicle.

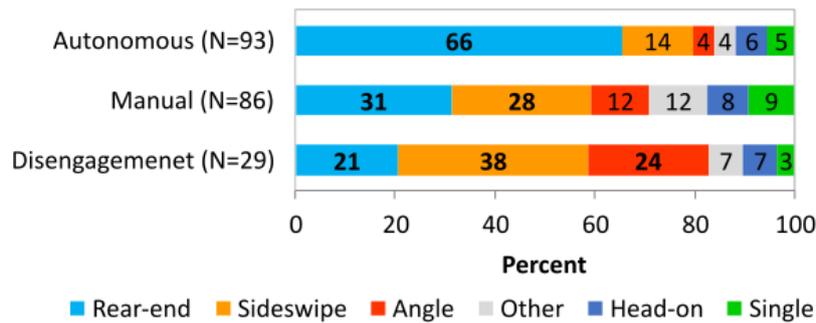


Figure 2 Collision types by AV mode

In most single vehicle collisions, the AV was in manual mode (57%). This indicates that automated mode is most reliable in the absence of other road users. All single collisions were with fixed objects.

3.8 Collisions with VRU

In collisions between an AV and a vulnerable road user ($n = 20$), the VRU (cyclist, skateboarder or e-scooterist) was at-fault in 16 collisions (80%); for the remaining four VRU-collisions information about who was at-fault is missing.

In most VRU-collisions, the AV was in manual mode (45%), followed by disengagements (35%). The odds of occurring right after disengagement was far higher in VRU-collisions than in other collisions (306%, CI [46%; 1028%]). The AV was in autonomous mode in four VRU-collisions (20%).

Most VRU-collisions occurred at intersections (75%). From 2021 to 2022, the share of VRU-collisions is about doubled (from 7% to 13% of all collisions, based on 8 and 13 VRU collisions in 2021 and 2022, respectively).

3.9 Collisions in disengagement mode

After disengagement, the odds of being at-fault was about as high as in manual mode (-31%, CI [-75%; +92%]). Typical disengagement collision types were sideswipe and angle midblock collisions where the AV driver disengaged to solve a critical traffic situation. VRUs were overrepresented in disengagement collisions.

4 Conclusions

Our findings confirm results from earlier studies regarding the most frequent collision types and consequences. Additionally, they show that driving in autonomous mode was significantly related to rear-end collisions and other collisions where the collision partner is at-fault, but not to single collisions. A possible explanation is that AVs in autonomous mode ‘behave’ differently from manually driven cars, and thus more unpredictable for other road users.

The total number of collisions per six months is about doubled from 2021 to 2022, which may be attributed to increased AV testing. Collision rates could not be compared due to missing data on MVKT from 2022.

A comparison between 2021 and 2022 indicates that the share of collisions in autonomous mode and the share of rear-end collisions have increased, although there was no increase in the share

of rear-end collisions in autonomous mode. The increase of collisions in autonomous mode may be related to the development of AV technology, which allows driving in automated mode more frequently.

The share of VRUs involved in collisions has also increased from 2021 to 2022. Although the comparison is based on relatively few collisions, this requires extra attention, as AVs are going to encounter VRUs more and more frequently. VRUs present specific challenges for AVs, because they are often less predictable and more difficult to detect than cars.

CRedit contribution statement

Petr Pokorny: Conceptualization, Data curation, Methodology, Formal analysis, Writing—original draft. **Alena Høye:** Formal analysis, Writing—review & editing.

Declaration of competing interests

The authors report no competing interests.

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