Automated Driving System Testing in California

Trends in Collision and Disengagement Data

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MISSION STATEMENT

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Executive Summary

The disengagement and collision reports submitted to the California Department of Motor Vehicles (CA DMV) by entities testing Automated Driving Systems (ADS) equipped vehicles with a safety driver in California provide a valuable source of data that can be used by regulators, academics, and the public to gain insights into the development and operations of ADS.[1] This report compares California's regulations for ADS testing with a safety driver to five other states' regulations. It analyzes self-reported disengagement and mileage totals for ADS equipped vehicles testing in California between 2014 and 2018 and collisions involving ADS equipped vehicles which occurred on or before April 14, 2019. Key findings from the team's research and analysis include:

- Rear-end collisions are the most frequently reported collision type for ADS equipped vehicles in autonomous mode
    - In collision reports submitted by testing entities, collisions were described as rear end, side swipe, hit object, other, broadside, head on, or vehicle pedestrian
    - Rear-end collisions made up 72% of reported collisions in autonomous mode

- The majority of collisions in autonomous mode reportedly resulted in minor damage
    - Collision damage was described as major, moderate, minor, or none
    - Approximately 78% of collisions resulted in minor damage

- All reported collisions occurred within the Bay Area
    - Most Cruise collisions occurred in downtown San Francisco and most Waymo collisions occurred around Mountain View
    - Approximately 97% of collisions occurred on an urban street

- Large numbers of a sample of 2018 disengagements listed issues with the ADS technology in the disengagement cause description
    - Software, planning, and perception discrepancy were each reported in disengagement causes signficantly more than other words or phrases
    - Most of the disengagement cause descriptions which mentioned an object did not describe what the object was
    - External factors such as traffic lights or lane markings occurred much less frequently

- There are significant differences in the requirements that companies must meet to test ADS with a safety driver from state to state
    - While the permitting process in California is similar to other states, test driver certification is generally more comprehensive
    - Of the six states compared in this report, disengagement reporting is unique to California, and only California and Pennsylvania require that entities simulate road testing conditions in a controlled environment

[1] A disengagement is a deactivation of autonomous mode when a failure of the autonomous technology is detected or when the safe operation of the vehicle requires that the ADS test driver disengage the autonomous mode and take immediate manual control of the vehicle; "Article 3.7", State of California (2019), https://www.dmv.ca.gov/portal/uploads/2020/06/Adopted-Regulatory-Text-2019.pdf.

ADS Regulation Across the United States

The U.S. Department of Transportation (USDOT) has issued several policy documents which provide guidance to ADS manufacturers, law enforcement, state governments, and the general public: *Federal Automated Vehicles Policy* (2016), *Automated Driving Systems 2.0* (2017), *Automated Vehicles 3.0* (2018), and *Automated Vehicles 4.0* (2020). These documents outline the USDOT's view of the role that federal, state and local governments have in ADS regulation and offer best practices for states that permit ADS testing and deployment.[2] According to the USDOT, states are responsible for ensuring safety and mobility for road users in their jurisdictions.[3] This responsibility includes developing policies and laws guiding testing and operating ADS on public roadways.[4] USDOT notes that states may want to consider developing procedures and conditions for the introduction of ADS on public roadways, but does not expect this of states.[5]

As of March 23, 2020, 28 states and the District of Columbia have formally allowed ADS equipped vehicles to test with or without a human operator or deploy on public roads through executive order or legislative action, as shown in Figure 1.[6] Any states listed in Figure 1 as permitting testing without a human operator also permit testing with a human operator. Any states listed in Figure 1 as permitting deployment also permit testing with and without a human operator.

Figure 1: States and Districts Allowing Testing or Deployment of ADS Equipped Vehicles
Source: National Conference of State Legislatures, "Autonomous Vehicles | Self-Driving Vehicles Enacted Legislation" on March 23, 2020

Testing permitted only with a human operator	Testing permitted without a human operator	'Deployment' permitted without a human operator
Connecticut	Arkansas	Alabama
Illinois	Hawaii	Arizona
Maine	Ohio	California
Massachusetts	Washington	Colorado
New York		District of Columbia
Pennsylvania		Florida
Vermont		Georgia
Virginia		Iowa
		Louisiana
		Michigan
		Nebraska
		Nevada
		North Carolina

[2] US Department of Transportation (2017), https://www.nhtsa.gov/sites/nhtsa.dot.gov/files/documents/13069a-ads2.0_090617_v9a_tag.pdf.
[3] US Department of Transportation (2018), https://www.transportation.gov/sites/dot.gov/files/docs/policy-initiatives/automated-vehicles/320711/preparing-future-transportation-automated-vehicle-30.pdf.
[4] US Department of Transportation (2017), 22.
[5] Ibid.
[6] Truck platooning is not considered ADS testing for the purposes of this list. "Autonomous Vehicles", National Conference of State Legislatures (2019), http://www.ncsl.org/research/transportation/autonomous-vehicles-self-driving-vehicles-enacted-legislation.aspx.

		North Dakota Tennessee Texas Utah
Total: 8	Total: 4	Total: 16 + DC
Grand Total: 28 + DC		

This report reviewed and compared regulations for testing ADS equipped vehicles with a safety driver across California, Arizona, Massachusetts, New York, Nevada, and Pennsylvania. These states were selected for comparison based on their diverse regulatory approaches. Figure 2 below compares the six states' regulations for ADS testing with a safety driver across seven categories.[7] The permitting process varies across the states, ranging from multiple approvals and a fee to simple notification of intent to test. Safety driver certification ranges from no additional certification beyond a driver's license to a mandatory training program following state specifications. Most states listed in Figure 2 require collision reporting and allow ADS equipped vehicles on all public roads. Only California of the states considered requires disengagement reports in addition to collision reports. California and Pennsylvania are the only states of those considered to require entities to simulate road testing conditions in a controlled environment.

[7] Seven categories of comparison were created to describe ADS testing regulations, including "Permitting process" and "Collisions reporting." "Safety certification for test drivers" includes additional certification measures that apply to an individual who possesses an unrestricted driver's license, is trained in the operation of the ADS entity's vehicles, and is professionally affiliated with the entity. "Extent of authorized testing" describes the public roads on which ADS equipped vehicles are allowed to be used. "Local authority" describes the extent to which the state stipulates that ADS must comply with applicable local regulations. "Other reporting requirements" refers to descriptive information required by the state other than collision reports and permitting or permit renewal paperwork.

Figure 2: State Regulations for ADS Testing with Safety Driver[8]						
	California[9]	Arizona[10]	Massachusetts[11]	New York[12]	Nevada[13]	Pennsylvania[14]
Permitting process	Application with $3,600+ fee, vehicle information required, permit valid for two years, additional fee of $50 for every 10 vehicles or 20 safety drivers	Notification form	Application to test, testing plan, Memorandum of Agreement with participating municipalities	Application form for limited testing period, law enforcement interaction plan	Application packet, $101 fee for testing certificate fee and $13-$18.50 fee per vehicle	Notice of testing forms and "Safety Plan" or "Voluntary Safety Self Assessment," annual renewals required[15]
Safety certification for test drivers	Licensed to drive motor vehicle for preceding three years, does not have more than one violation point count per CA Vehicle Code, not at fault in collision causing injury/death, no convictions, suspensions, or revocations over preceding ten years due to vehicle operation under the influence of alcohol or drugs, completed CA "Autonomous Vehicle Test	No additional listed	21 years of age, no pending cases or conviction for operation of motor vehicle while under the influence of alcohol or drugs	Every test vehicle operator must be adequately trained in the safe operation of the test vehicle to ensure both legal and safe operation	No additional listed	Safety driver training program description in "Safety Plan" which includes confirmation of driving skills, understanding of ADS equipped vehicle controls and trip procedures, and measures to prevent inattentiveness; additional "safety associate" needed for

[8] In addition to existing non-AV standards and regulations across the state, with the exception of collisions as noted
[9] "Article 3.7", State of California (2019), https://www.dmv.ca.gov/portal/uploads/2020/06/Adopted-Regulatory-Text-2019.pdf.
[10] AZ Department of Transportation (2019), https://azdot.gov/motor-vehicles/professional-services/autonomous-vehicles-testing-and-operating-state-arizona.
[11] MA Department of Transportation (2019), https://www.mass.gov/how-to/how-to-test-automated-driving-systems-in-massachusetts.
[12] NY State DMV (2019), https://dmv.ny.gov/dmv/apply-autonomous-vehicle-technology-demonstration-testing-permit.
[13] NV DMV (2019), https://dmvnv.com/autonomous.htm and NV State Statutes (2017), https://www.leg.state.nv.us/NAC/NAC-482A.html.
[14] PA Department of Transportation (2018), https://www.penndot.gov/ProjectAndPrograms/ResearchandTesting/Autonomous%20_Vehicles/Documents/PennDOT%20HAV%20Testing%20Guidance.pdf.
[15] Safety plan requires information on testing location, disengagement technology, software and hardware validation, and safety driver training.

	Driver Training Program"					testing at speeds above 25mph
	California	Arizona	Massachusetts	New York	Nevada	Pennsylvania
Collisions reporting	Report within ten days any collision involving an ADS equipped vehicle; use Report of Traffic Collision Involving an Autonomous Vehicle, form OL 316 (REV 2/2017)[16]	State standard for all vehicles: report within 24 hours any collision involving death, injury, over $1000 in property damage, or issuance of a citation[17]	Report any collision involving ADS to Memorandum of Understanding (MOU) signatory parties within 24 hours, file an MOU Crash Report within five days, suspension of testing until cause of crash is determined and corrections are made or until all parties agree that the crash was minor or not a result of an ADS failure[18]	State standard for all vehicles: report within ten days of any collision involving death, injury, or over $1000 in property damage[19]	Report within ten business days of collisions involving property damage greater than $750, a traffic violation, or personal injury	Report within six hours any collision occurring when ADS is engaged; if a collision occurred while the ADS was not engaged it should be reported if the collision involved injury or death or if any vehicle involved was left unable to be driven; no indication needs to be given that a vehicle involved was ADS equipped[20]

[16] See Appendix 4
[17] AZ State Legislature (2019), https://www.azleg.gov/viewdocument/?docName=http://www.azleg.gov/ars/28/00667.htm.
[18] City of Boston (2019), https://www.boston.gov/sites/default/files/document-file-01-2017/template-mou-for-av-testing.pdf.
[19] NY State DMV (2019), https://dmv.ny.gov/dmv-records/crash-accident-reports.
[20] PA Department of Transportation (2020), https://www.penndot.gov/ProjectAndPrograms/ResearchandTesting/Pages/Autonomous-Vehicle-Testing-FAQs.aspx.

	California	Arizona	Massachusetts	New York	Nevada	Pennsylvania
Extent of authorized testing	No limit listed	No limit listed	Within 14 participating municipalities with unique regulations	No limit listed	No limit listed	No limit listed
Local authority	CA DMV issues statewide permit allowing public road testing in any California municipality. ADS must comply with all applicable local regulations "except when necessary to enhance the safety of the vehicle's occupants and road users"	Not specifically mentioned	Massachusetts Department of Transportation issues guidance, each municipality must opt-in via an MOU for testing to occur within the municipality	Not specifically mentioned	Local government explicitly prohibited from imposing a tax, fee, or other regulation on ADS	Local "municipality, city, or operating agency" may temporarily prohibit use of highly automated vehicles "for emergencies, special events or safety concerns"
Other reporting requirements	Disengagement reports and total test miles driven	None listed	Upon request, "information about safety issues, unexpected or unintended occurrences, data about roads, speeds, and miles traveled"; Boston requires quarterly reporting[21]	"Test/demonstration report" including dates, parameters, and locations of tests, autonomous miles traveled, and findings with road safety impact[22]	None listed	Semi-Annual Data Collection Form including mileage, roadway type, counties in which testing occurred, the number of in-state employees involved with testing, and if applicable, new jobs and facilities created in the state because of testing

[21] The city does not mandate the inclusion of any particular information in these reports, nonetheless most include information about locations in which testing occurred, total miles in autonomous mode, whether any crashes occurred, and software and hardware areas in which the entity has developed. See: https://www.boston.gov/sites/default/files/document-file-06-2019/optimus_ride_-_quarterly_report_-_q1_2019.pdf and https://www.boston.gov/sites/default/files/document-file-05-2019/nutonomy_q1_2019.pdf.

[22] NY State DMV (2019), https://dmv.ny.gov/forms/av1.pdf.

	California	Arizona	Massachusetts	New York	Nevada	Pennsylvania
Other state actions	Must simulate expected road testing conditions in a controlled environment before initiating road testing	State-funded research institute[23]	None listed	Police escort required[24]	None listed	Must simulate expected road testing conditions in controlled environment before initiating road testing

[23] Randazzo (2018), https://www.azcentral.com/story/money/business/tech/2018/10/11/arizona-institute-automated-mobility-created-self-driving-cars/1594941002/.

[24] Cheromcha (2017), https://www.thedrive.com/tech/8979/new-york-to-approve-self-driving-car-testing-on-public-highways.

ADS Testing in California

California has been a hub for ADS development since 2009.[25] The state's abundance of universities, proximity to technology entity headquarters, and mild weather make it an ideal testing ground for ADS. In 2014, the California State Legislature passed Senate Bill No. 1298 that directed the CA Department of Motor Vehicles (CA DMV) to adopt regulations for the testing of ADS on public roads.[26] Per the California Vehicle Code, Section 38750-38755, in 2012, the CA DMV established the Autonomous Vehicle Testing Regulations and subsequently created three permits which allow entities to test ADS equipped vehicles with a safety driver on public roads, test without a driver on public roads, and deploy their vehicles on public roads.[27]

Over the last 10 years, the number of entities testing ADS with a safety driver on California public roads has grown substantially.[28] In 2015, seven entities were permitted for testing ADS with a safety driver on California roads. By the end of 2018, 62 entities were permitted to test ADS on public roads with a safety driver and 37 of those were actively testing ADS with a safety driver. Only one entity had been permitted to test ADS equipped vehicles without a safety driver by the end of 2018.[29] This report will consider data from the entities testing ADS on public roads with a safety driver.

The CA DMV requires entities testing ADS equipped vehicles with a safety driver or without a safety driver to submit a collision report in the event of a crash. Entities testing ADS must also provide to the CA DMV reports of disengagements caused by "a deactivation of the autonomous mode when a failure of the autonomous technology is detected or when the safe operation of the vehicle requires that the ADS test driver disengage the autonomous mode and take immediate manual control of the vehicle."[30] Entities that receive a deployment permit must adhere to a different set of requirements and are no longer required to report disengagements and every collision to the CA DMV; however, collisions reaching specified thresholds in terms of personal injury and/or property damage may still require reporting under laws applicable to all motor vehicles.[31]

This report analyzes California collision and disengagement reports filed between October 14, 2014 and April 14, 2019 (report period) to gain insight into the development and current state of ADS technology testing on California's roadways. All collisions during the report period were analyzed and a sample of 2018 disengagements were selected for further examination. The disengagement sample selection includes 1,507 disengagement reports from 21 permitted entities and was limited due to time constraints of the research team and data availability. More information about the

[25] Markoff (2010), https://www.nytimes.com/2010/10/10/science/10google.html.
[26] CA State Legislature (2012), https://leginfo.legislature.ca.gov/faces/billNavClient.xhtml?bill_id=201120120SB1298.
[27] Deployment is the public use of ADS equipped vehicles, Cal. Veh. Code § 38750-38755 (2017), https://leginfo.legislature.ca.gov/faces/codes_displayText.xhtml?lawCode=VEH&division=16.6
[28] CA DMV (2019), https://www.dmv.ca.gov/portal/dmv/detail/vr/autonomous/disengagement_report_2018.
[29] CA DMV (2018), https://www.dmv.ca.gov/portal/dmv/detail/vr/autonomous/driverlesstestingpermits.
[30] "Article 3.7", State of California (2019), https://www.dmv.ca.gov/portal/uploads/2020/06/Adopted-Regulatory-Text-2019.pdf.
[31] "Article 3.7", State of California (2019), https://www.dmv.ca.gov/portal/uploads/2020/06/Adopted-Regulatory-Text-2019.pdf., "CHAPTER 1. Accidents," California Legislative Information. https://leginfo.legislature.ca.gov/faces/codes_displayText.xhtml?lawCode=VEH&division=10.&title=&part=&chapter=1.&article=.

selection process for the sample is described below. All collision and disengagement information used in this report was reported to the CA DMV by the entities testing ADS equipped vehicles.

Disengagement Reporting Background

The annual disengagement reports submitted by all entities testing ADS equipped vehicles with safety drivers in California contain information about each individual disengagement as well as summary information about each ADS equipped vehicle operated by the entity. The annual disengagement reports cover the period from December 1 through November 30 of each year (for example, "2017 disengagement reports" cover the period between December 1, 2016 and November 30, 2017). This paper will use the December through November "year" in all analysis presented above and below.

The CA DMV's initial regulations governing ADS testing went into effect September 16, 2014.[32] The disengagement reporting standards in these regulations required ADS manufacturers to provide specific information for each disengagement reported: the road type, a description of the cause of disengagement, and the time elapsed from when the driver was notified of technology failure to achieving manual control of the vehicle. However, there was no standard reporting format for these reports, making analysis challenging. In 2015, seven manufacturers filed disengagement reports, increasing to 20 by 2017. In April of 2017, the CA DMV released a new form OL 311R to shift to more standardized disengagement reporting which removed the time elapsed category.[33] Some manufacturers did not adopt the new form for their 2017 disengagement reporting, making it difficult to compare 2018 and pre-2018 disengagement reports. By 2018, most manufacturers were reporting the same information on disengagements through the OL 311R form.

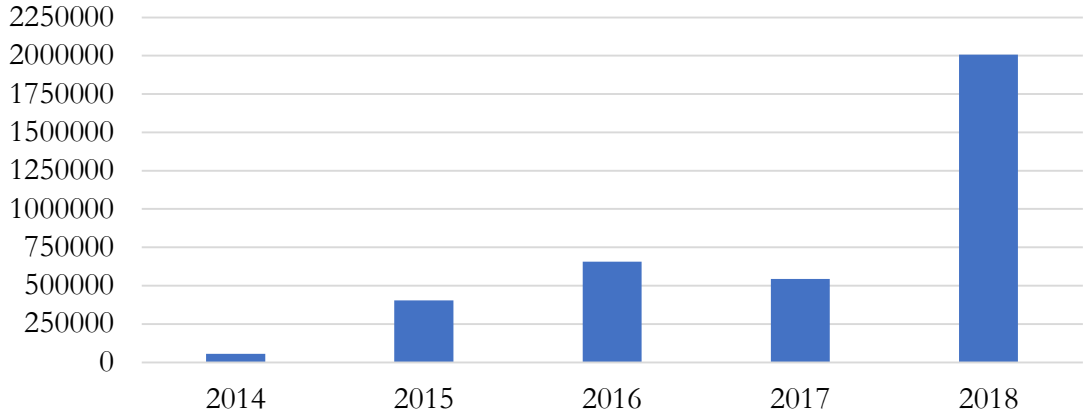
The OL 311R released in April 2017 requires entities to submit the following information:

- Whether an ADS is capable of operating without a driver
- Road type where the disengagement occurred (i.e. street, highway, parking lot)
- Whether a safety driver was present[34]
- Whether the ADS or a safety driver initiated the disengagement
- Detailed "description… written in plain language" of the reason for the disengagement[35]
- Monthly total miles in autonomous mode
- Disengagement totals

Disengagement Report Analysis

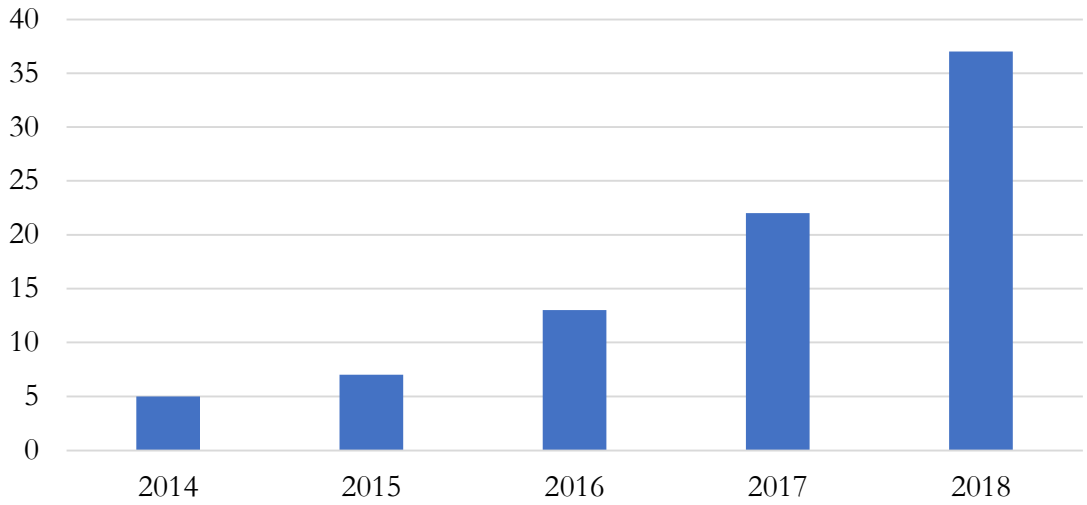
[32] CA DMV (2019), https://www.dmv.ca.gov/portal/dmv/detail/vr/autonomous/testing.
[33] CA DMV (2020), https://www.dmv.ca.gov/portal/vehicle-industry-services/autonomous-vehicles/disengagement-reports/.
[34] The OL 311R form is also used to report disengagements which occur in ADS equipped vehicle testing without a safety driver. CA DMV (2019), https://www.dmv.ca.gov/portal/dmv/detail/vr/autonomous/auto.
[35] "Article 3.7", State of California (2019), https://www.dmv.ca.gov/portal/uploads/2020/06/Adopted-Regulatory-Text-2019.pdf.

Figure 3: ADS Total Miles in Autonomous Mode



Source: CA DMV Disengagement Reports 2015-2019

Figure 4: Number of Entities Logging Autonomous Testing Miles

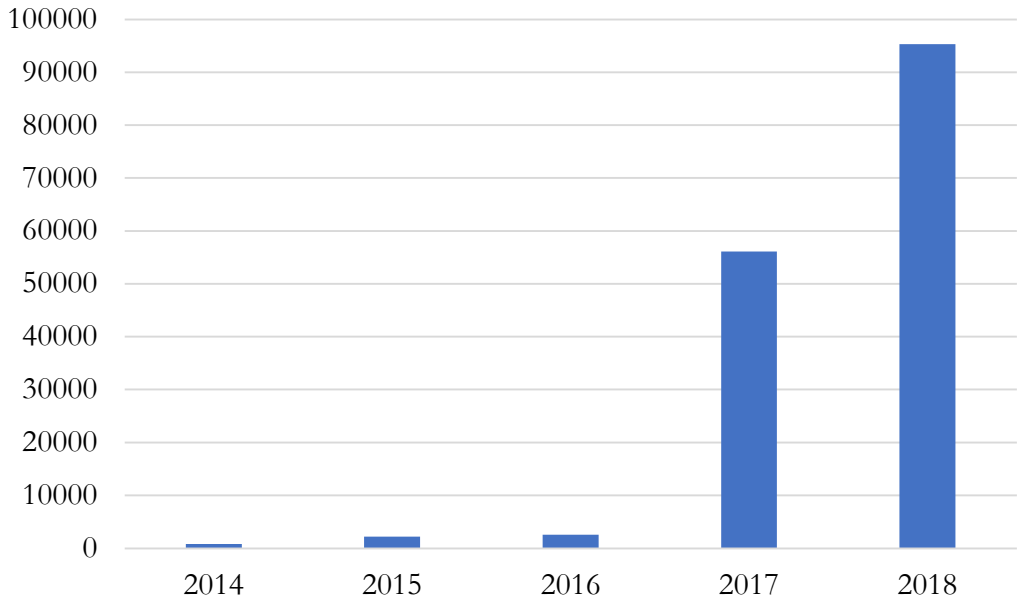


Source: CA DMV Disengagement Reports 2015-2019

As seen in Figures 3 and 4, in 2014 there were five entities reporting testing mileage totaling approximately 56,000 miles.[36] By 2018, the number of entities reporting testing mileage increased to 37, testing over 2,000,000 miles in autonomous mode. Increased numbers of entities testing did not strictly correlate with increased testing miles, as in 2017 the number of miles fell despite an increase in the number of entities reporting testing mileage. Despite the number of entities testing, Waymo LLC (Waymo) accounted for approximately 79% of the total miles operated in 2014.[37] By 2018, with many more entities testing, Waymo still accounted for approximately 63% of total miles.[38]

[36] See Appendix 1 for total entities, miles, disengagements, and collisions.
[37] Google's ADS program is officially listed as Waymo in later reports.
[38] See Appendix 2 for Waymo total miles, disengagements, collisions, and percent of total miles.

Figure 5: ADS Total Disengagements



Source: CA DMV Disengagement Reports 2015-2019

Figure 5 shows the disengagement totals for entities testing in California between 2014 and 2018. Total disengagements increased from 794 in 2014 to 95,295 in 2018. The number of disengagements in 2017 and 2018 were substantially higher than in 2014, 2015, or 2016. Total disengagements increased significantly between 2016 and 2017 despite an overall decrease in autonomous miles.

Additional analysis was conducted on a sample of individual disengagements. The aim of the sample analysis was to learn more about the type of information disengagements provide. In particular, the sample analysis attempted to determine what disengagements can tell us about some ADS equipped vehicles' ability to identify and correctly respond to roadway features such as traffic control devices and other roadway users. All disengagements in the sample were drawn from 2018 so that the type of information reported for each disengagement would be the same across entities.[39]

The sample was made up of entities that had less than 500 individual disengagements, provided relatively detailed cause descriptions, and had published individual disengagement information for 2018 by April 2019. Any entity with more than 500 individual disengagements would have been unmanageable for the research team given time constraints. Also, given the small sample size, including disengagements from an entity with more than 500 individual disengagements would have overrepresented that company in the sample. The sample chosen ultimately included 1,507 disengagement reports from 21 permitted entities.[40] Figure 6 groups the disengagements in the sample by cause. In cases in which there were obvious typos in the cause descriptions, the typos

[39] CarOne LLC (Udelv) only provided month/year dates and Qualcomm Technologies, Inc. did not provide individual disengagement information for all of the disengagements they list in their 2018 summary.

[40] Entities included in the sample: AImotive Inc, AiPod, Aurora, AutoX Technologies Inc, Baidu, BMW, CarOne LLC (Udelv), Drive.ai, Inc., GMCruise, Nissan, Nullmax, Nuro, Phantom AI, Pony.Ai, Qualcomm Technologies, Inc., Roadstar.Ai, SF Motors, Telenav, Waymo, WeRide Corp (Jingchi), Zoox. See Appendix 3 for the number of disengagements in the sample per entity. Not all disengagements reported by each entity were incorporated in the sample because of the research team's time constraints.

were corrected. However, similar but not identical phrasings were left separate to highlight the unstandardized nature of the disengagement reports.

Figure 6: Number of Reported Disengagements by Reported Cause in Sample Source: CA DMV Disengagement Reports 2018	
Causes	Number
Total Disengagements	1507
Planning Discrepancy	242
Perception Discrepancy	161
Disengage for unwanted maneuver of the vehicle that was undesirable under the circumstances	87
Control Issue: Test Vehicle is programmed to keep a pre-set time gap behind Closest In Path Vehicle (CIPV or Vehicle In-Front). Cars cut in between CIPV and Test Vehicle. Test Vehicle initiated harsh braking to accommodate. Test Driver disengaged to keep up with traffic.	48
Other road user behaving poorly	46
Invalid object detection result	44
Precautionary takeover to address planning	39
New Feature Validation	35
Invalid traffic light result	34
Software discrepancy	34
Disengage for undesired motion planning behavior	32
Precautionary Takeover: Test Vehicle was not slowing down enough. Test Driver braked to keep safe distance from Closest In-Path Vehicle (CIPV or Vehicle In-Front)	31
Invalid decision making result	28
Invalid HD map information	26
Incorrect behavior prediction of other traffic participants	27
Perception Issue: Perception System did not detect lane due to poor lane marking and Test Vehicle did not stay in line. Test Driver disengaged to center the vehicle.	23
Planned test of technology	21
Planning discrepancy, insufficient slowing approaching lead vehicle.	21
Control Discrepancy	20
Invalid prediction result (Other vehicle unexpected or violated traffic rule)	19
Disengage for a perception discrepancy for which a component of the vehicle's perception system failed to detect an object correctly	19
Failed lane change maneuver	16
Precautionary Takeover: Test Vehicle was not performing optimally given heavy traffic condition. Test Driver disengaged as a precautionary measure to address traffic conditions and log issue for further examination.	16
Disengage for a recklessly behaving road user	16

Control Issue: Lateral Control performance was not ideal at the time, causing Test Vehicle to oscillate within lane and needed fine tuning. Test Driver disengaged to log issue for further examination.	14
Irregularity in hardware	11
Lane change maneuver failed, caused by trajectory planning	11
Control Issue: Lateral Control performance was not ideal on highway setting at the time, causing Test Vehicle to oscillate within lane and needed fine tuning. Test Driver disengaged to log issue for further examination.	10
Localization divergence	10
Invalid perception result (Unexpected pedestrians)	10
Perception Issue: Lane Detection in Perception system was not performing optimally, affecting Lateral Control performance, causing Test Vehicle to oscillate within lane and needed fine tuning. Test Driver disengaged to log issue for further examination.	10
Unwanted maneuver or stop by vehicle	9
Perception discrepancy, no object detection of lead vehicle.	9
Precautionary Takeover: Vehicle cut too close in front of Test Vehicle. Test Driver disengaged to address unanticipated traffic condition.	9
Detection error in perception system	9
Software module froze. As a result, Driver safely disengaged and resumed manual control.	9
Malfunction of hardware system	8
Invalid localization result	8
Hardware discrepancy	8
Planning discrepancy, insufficient slowing approaching red traffic light.	8
Software Issue: Planning software exited unexpectedly.	7
Discrepancy in high definition map build caused an undesired behavior	6
Hardware error	6
Another vehicle approached from behind	5
Invalid motion planning result	5
Planning & Control Issue: Test Vehicle's planned path is too close to adjacent lane causing the Test Vehicle to be off-centered. Disengaged to center the vehicle.	5
Perception Issue: Perception System did not detect lane due to poor lane marking with sunlight reflecting off the road and Test Vehicle did not stay in line. Test Driver disengaged to center the vehicle.	4
Vehicle control problem	4
Sensor Delay: Harsh braking situation with Closest in Path Vehicle (CIPV or Vehicle in Front). Sensor delay caused delay in braking. Disengaged to keep safe distance from CIPV.	4
Planning discrepancy, inappropriate acceleration and trajectory.	4
Perception Issue: Vision system (Camera and related software) was unable to detect lanes. Disengaged to record issue for further analysis.	4
Lane change maneuver failed, caused by lane detection problem	4

Perception Issue: Lidar system false detected object. Test Driver disengaged to log issue for further examination.	4
Precautionary Takeover: Traffic Light turned Red, Test Vehicle was not slowing down enough. Test Driver braked as a precaution.	3
Perception Issue: Unable to detect adjacent lane, lane change was unsuccessful. Disengaged to log the issue.	3
Disengage for adverse weather conditions experienced during testing	3
Planning discrepancy, inappropriate trajectory with adjacent vehicle.	3
Irregularity in AV system	3
False perception of traffic light caused AV to proceed at red light	3
Perception discrepancy, no object detection.	3
Planning discrepancy, inappropriate trajectory with nearby pedestrian.	3
All other causes	183

The disengagement causes shown in Figure 6 vary widely, including hardware and software failures of the ADS equipped vehicle, local weather conditions, inability to detect road features such as traffic lights and lane markings, and planning discrepancies related to pedestrians. The causes are also inconsistent across companies. Some causes include relatively detailed information about the ADS equipped vehicle's software failure, while many of the causes are only a few words long or formulaic, as in "Software discrepancy" and "Planning Discrepancy." Some causes offer almost no information, such as "Disengage for unwanted maneuver of the vehicle that was undesirable under the circumstances." It is unclear what the circumstances were and what behavior might qualify as undesirable. Multiple disengagement causes reference inappropriate ADS behavior near a traffic light, with slowing down sufficiently appearing to be a particular challenge. Objects in the roadway also caused several disengagements, though the majority of cause descriptions do not specify what those objects were.

Collision Reporting Background

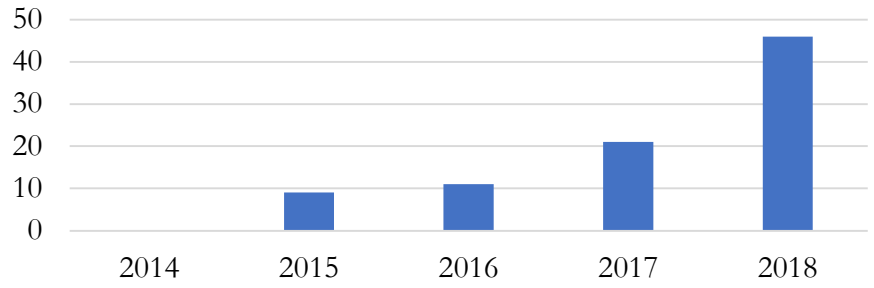
The CA DMV requires entities testing ADS equipped vehicles on public roads to report all collisions involving their respective ADS equipped vehicles using the form OL 316 (REV 2/2017) reproduced in Appendix 4.[41] The form requests information about "all persons involved in the collision" and calls for "a full description of how the collision occurred." The form includes standard collision reporting information such as vehicle type, damage location, and injuries sustained. It also includes a variety of categories designed to assess the circumstances of a collision. These categories range from time and location to movement before and during the collision for each vehicle involved. The CA DMV regulations also specify that any and all other regulations regarding collision reporting for a non-ADS vehicle still apply in the case of ADS equipped vehicle collisions. Collision reporting requirements have remained mostly unchanged since they were first adopted. However, in the spring of 2018, the CA DMV updated the collision form to include more categories for information about environmental conditions at the time of the collision.[42]

[41] "Article 3.7", State of California (2019), https://www.dmv.ca.gov/portal/uploads/2020/06/Adopted-Regulatory-Text-2019.pdf.

[42] In April 2018 all entities began to report the weather, lighting, roadway surface, and roadway conditions at the time and location of the collision.

Collision Analysis

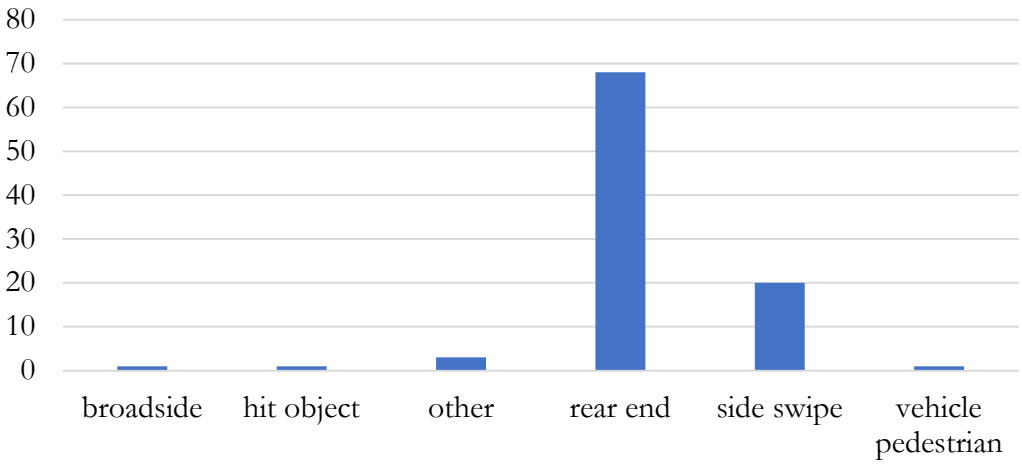
Figure 7: Total Number of Collisions in Autonomous Mode



Source: CA DMV Collision Reports 2015-April 14, 2019

Figure 7 shows all reported autonomous mode collisions between 2014 and 2018. In 2014, there were no collisions in autonomous mode with approximately 56,000 miles driven. In 2018, there was on average one collision per 44,000 miles driven. In general, as testing miles in autonomous mode increased, so did collisions. The number of collisions increased every year, despite a decrease in testing miles in 2017. In total, 152 collisions occurred. 94 collisions occurred while the ADS equipped vehicle was in autonomous mode and 58 occurred while the ADS equipped vehicle was in conventional mode.

Figure 8: Number of Autonomous Mode Collisions by Type



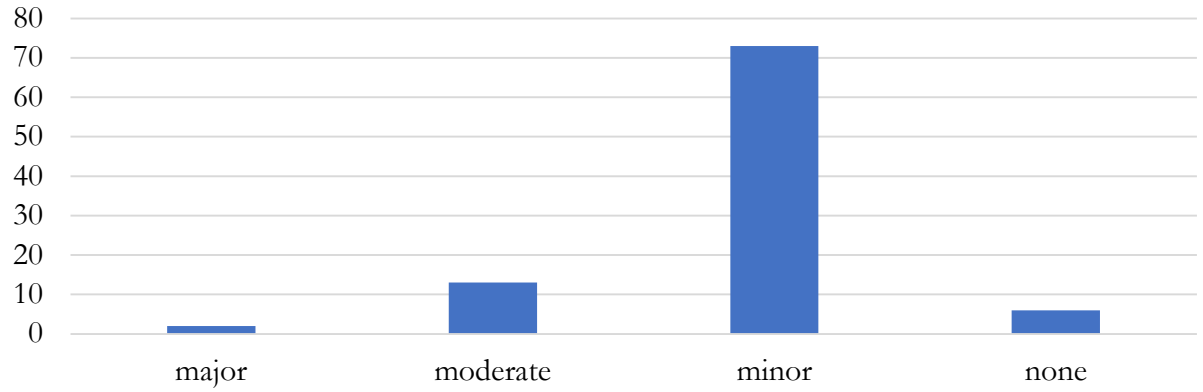
Source: CA DMV Collision Reports 2014-April 14, 2019

Figure 8 shows the distribution of collision types across the 94 autonomous mode collisions.[43] The most common autonomous mode collision type was a rear ending, representing approximately 72% of the total autonomous mode collisions. The next most common type of collision was side swipe, representing approximately 21% of all autonomous mode collisions. Only one collision each of broadside, vehicle pedestrian, and hit object were reported for ADS equipped vehicles in autonomous mode. No autonomous mode collisions were reported as head on. All collisions in the

[43] Appendix 5 shows collision types by autonomous and conventional mode. Not all collision reports included a collision type. When a collision type was not listed, the collision description and damage location listed in the collision report were used to fill in the collision type.

report period which are identified as a rear ending involved another vehicle striking the rear of the ADS equipped vehicle. However, there was some inconsistency in reporting other types of collisions. For example, there were two instances in the collision reports in which an ADS equipped vehicle hit the side of another vehicle. In one instance, "a vehicle backing out of a parking spot made contact with the Waymo AV's driver's-side sliding door and rear quarter panel at approximately 2 mph". The collision was reported as a "broadside". Another collision was described as "a parked vehicle pulled out in front of the Cruise AV making contact with the Cruise AV's passenger side door causing light damage on both the front and rear passenger side door panels". This collision was reported as a "side swipe". Collision cause does not appear to be standard and varies by the entity filling out the report.

Figure 9: Number of Autonomous Mode Collisions by Damage Type



Source: CA DMV Collision Reports 2014-April 14, 2019

Figure 9 shows the frequency of types of damage reportedly caused to the ADS equipped vehicle in the collisions studied.[44] The collision report forms do not specify the distinction between damage types, giving entities discretion to report whichever damage type they determine is most appropriate. In some cases, entities did not report a damage type. Minor damage leads all other categories by a substantial margin, with approximately 78% of collisions resulting in minor damage. Moderate, none, and major damage are all less prevalent than minor damage. Moderate damage occurred in approximately 14% of the collisions, no damage occurred in approximately 6% of collisions, and major damage in approximately 2% of collisions.

Figure 10 shows the primary other party involved in autonomous mode collisions.

Figure 10: Other Parties in Autonomous Mode Collisions
Source: CA DMV Collision Reports 2014-April 14, 2019

Other party	Number of collisions
None	1
Pedestrian	2
Motorcyclist	2
Bicyclist	3
Vehicle	86

[44] Appendix 5 shows collisions by damage type. Not all collision reports included a damage type. When a damage type was not listed, the collision description listed in the collision report was used to fill in the damage type.

Total	**94**

The vast majority (approximately 91%) of autonomous mode collisions were between the ADS equipped vehicle and another vehicle. All other party types including those shown in Figure 10 below were involved in less than 3% of the autonomous mode collisions. Damage information is not included in the collision reports for parties other than the ADS equipped vehicle. However, some reports include whether an injury occurred, and the mode of the other party injured (driver, motorcyclist, passenger etc.). Of the 94 autonomous mode collisions, nine other parties were reportedly injured. Of these other injured parties, six were drivers, two were passengers, and two were cyclists. No pedestrians were reportedly injured.

Figure 11 shows all reported collisions (autonomous and conventional mode) involving an ADS equipped vehicle in California over the report period. Collisions are marked by dots colored to reflect the ADS equipped vehicle's permit holder. All collisions occurred in the Bay Area, primarily in downtown San Francisco and in Mountain View. Only five collisions occurred on non-urban streets, with three on a non-urban highway and two on rural or other roads. Entities' collisions are often grouped in a particular area, such as Mountain View or downtown San Francisco.

Figure 12 on the following page shows all reported collisions in the San Francisco area. Cruise and Waymo account for the majority of the collisions. These two companies also account for the majority of autonomous testing miles per their disengagement reports. Most Cruise collisions occur in downtown San Francisco, while most Waymo collisions occur around Mountain View. Of the entities with a smaller number of collisions, Zoox collisions are mostly located in downtown San Francisco and Lyft collisions are mostly located around Mountain View. The other entities listed had less than three collisions each.

Figure 11: Map of ADS Equipped Vehicle Collisions by Manufacturer
Source: CA DMV Collision Reports 2015-April 14, 2019

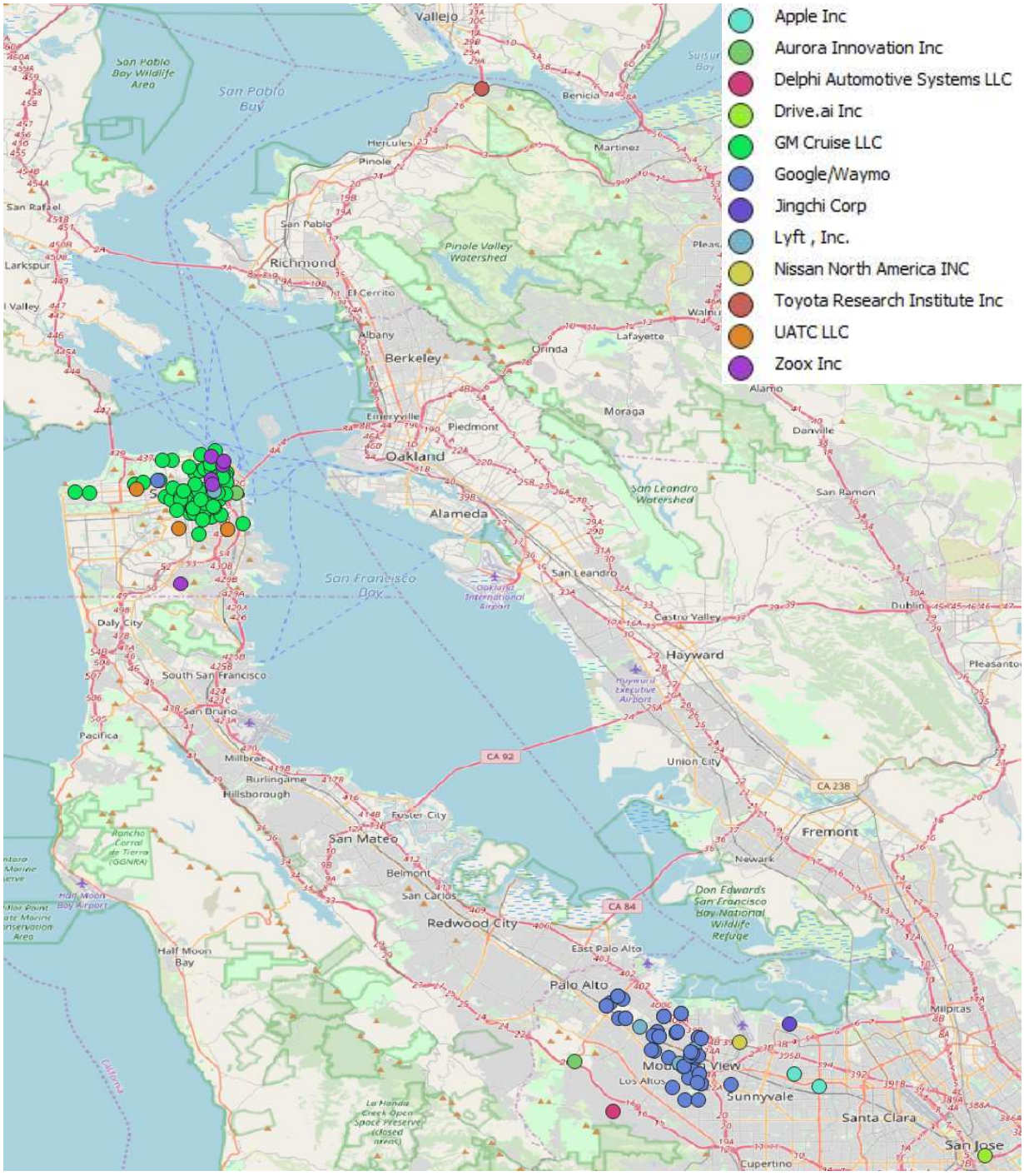
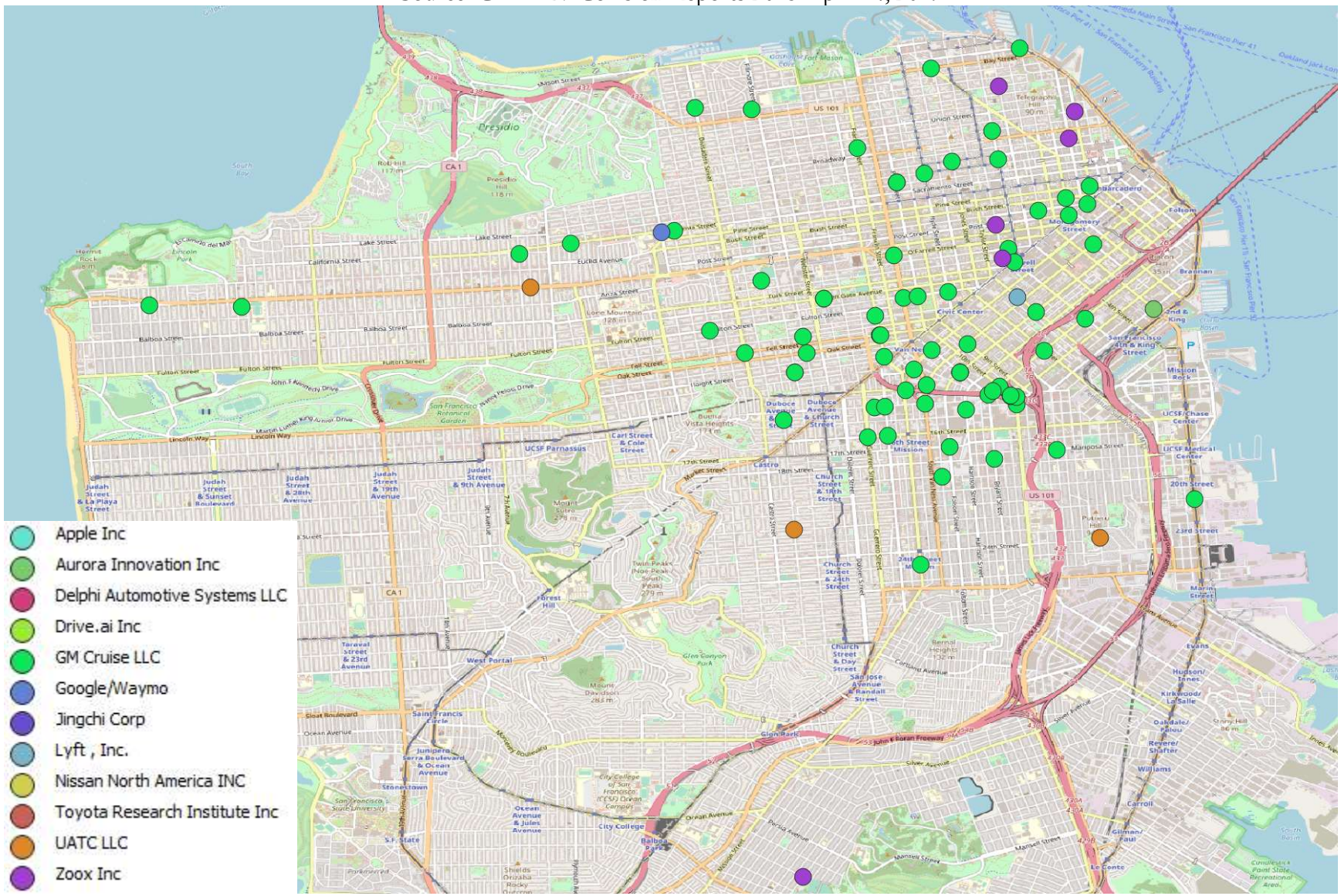


Figure 12: Map of ADS Equipped Vehicle Collisions by Manufacturer – San Francisco Detail
Source: CA DMV Collision Reports 2015-April 14, 2019



Considerations

Collision reports provide useful information such as the location, time, type, and severity of collisions involving ADS equipped vehicles. According to the collision reports collected by the CA DMV, 78% of autonomous mode collisions resulted in minor damage, with a handful of others resulting in no damage. Additionally, 72% of autonomous collisions were rear endings in which the ADS equipped vehicle was struck from behind by another road user. Rear end collisions often occurred when the ADS equipped vehicle was slowing or stopped near an intersection. While we have no data on speed at time of impact, it is reasonable to assume that many of these rear end collisions occurred at low speeds, potentially explaining why so many collisions resulted in minor damage. Collision type was reported inconsistently across entities testing ADS equipped vehicles and there are no thresholds for damage type, which also sometimes goes unreported. Permittees may benefit from additional guidance from the CA DMV to advance greater standardization of reporting across companies.

Collisions primarily occurred in downtown San Francisco and Mountain View. This could be a result of most testing occurring in these locations. However, the prevalence of collisions in these locations might suggest that these locations are particularly challenging for ADS. For example, these locations likely have high traffic density and complex road environments. Additional insights about collisions cannot be drawn without more information, such as where ADS test miles are occurring.

Considerable discrepancies exist between disengagement causes reported by entities testing ADS equipped vehicles. These discrepancies make disengagement cause analysis that could be useful to regulators, academics and the public challenging. Self-reported descriptions of disengagement causes range from two-word standard responses (i.e. planning discrepancy or perception discrepancy) to a more detailed account of what occurred. Disengagement analysis would benefit from greater standardization and greater detail in the cause descriptions.

More standardized disengagement reports could, for example, help clarify whether the objects which caused some disengagements were road debris, animals, pedestrians or cyclists and that, perhaps, we should be paying close attention to the disengagements involving objects that are humans. Overall, it is difficult to conduct additional analysis on disengagement data because the causes are not standardized across entities and, in some cases, the causes provide little information or context about the disengagement reported.

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Appendixes

Appendix 1

Figure 13: ADS Testing in California Source: CA DMV Disengagement Reports 2015-2019 and Collision Reports 2015-April 14, 2019				
Year	Total entities logging mileage	Total miles in autonomous mode	Total disengagements	Total collisions in autonomous mode
2014	5	55,999.61	794	0
2015	7	404,310.99	2,183	9
2016	13	657,034.75	2,547	11
2017	22	543,264.68	56,090	21
2018	37	2,007,405.41	95,295	46

Appendix 2

Figure 14: Waymo, LLC ADS Testing in California Source: CA DMV Disengagement Reports 2015-2019 and Collision Reports 2015-April 14, 2019				
Year	Total Waymo miles in autonomous mode	Total Waymo disengagements	Total Waymo collisions in autonomous mode	Waymo percent of total autonomous mode miles out of all autonomous mode test miles in CA
2014	44,014.90	42	0	78.60
2015	380,316.10	299	9	94.07
2016	635,867.90	124	9	96.78
2017	352,544.60	63	1	64.89
2018	1,255,997.4	114	18	62.57

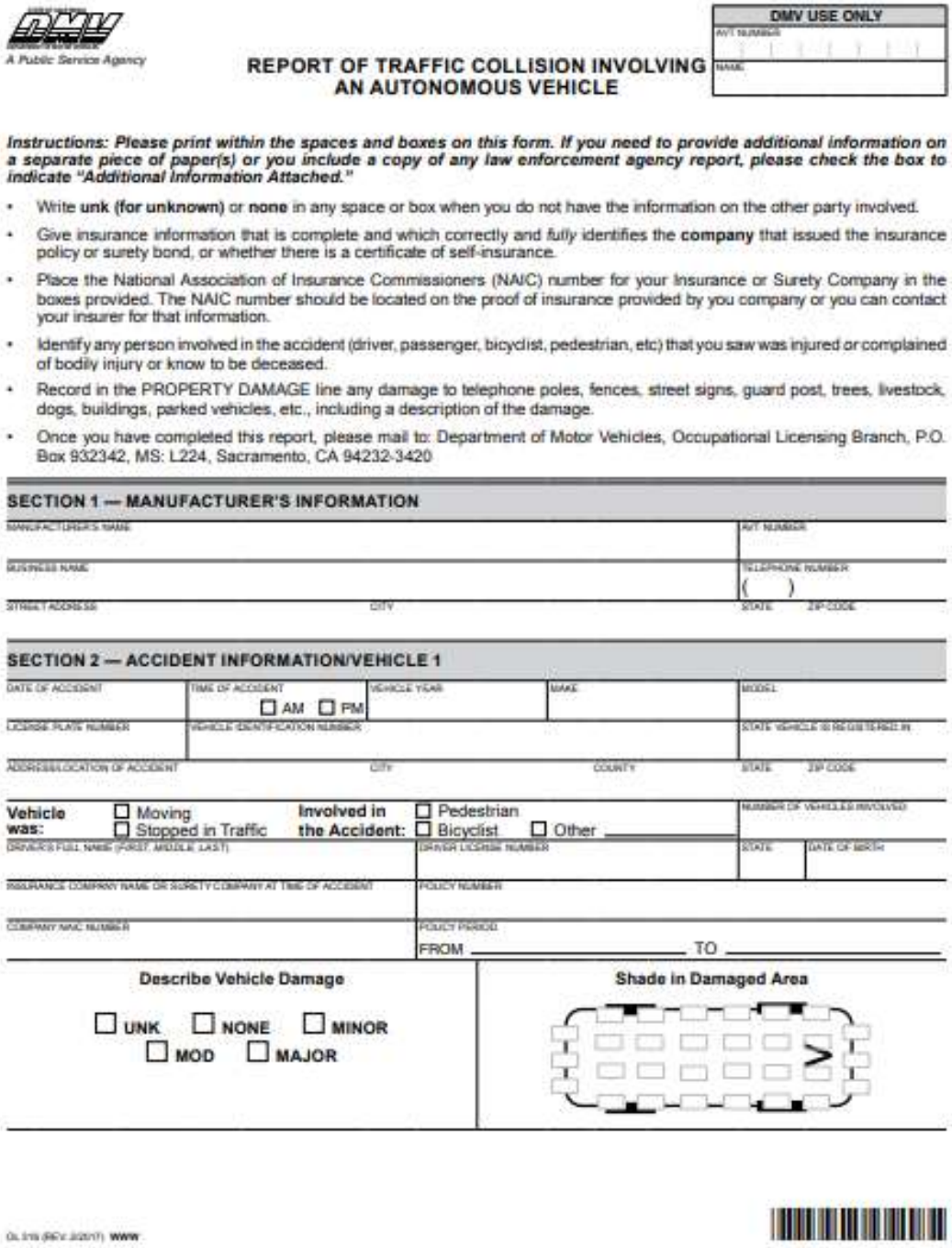
Appendix 3

Figure 15: Disengagement Cause Sample Entities and Number of Disengagements Source: CA DMV Disengagement Reports 2018	
Entity	Number of Disengagements
AImotive Inc	17
aiPod, Inc.	16
Aurora Innovation	307
AutoX Technologies Inc	119
Baidu USA LLC	88
BMW	9
CarOne LLC (Udelv)	57
Drive.ai, Inc.	55
GM Cruise LLC*	86
Nissan	26
Nullmax	68
Nuro, Inc	24
Phantom AI	200
Pony.AI	16
Qualcomm Technologies, Inc.	21
Roadstar.Ai	43
SF Motors Inc.	222
Telenav, Inc.	5
Waymo LLC	87
WeRide Corp (Jingchi)	25
Zoox, Inc.	16
Total	1507

* GM Cruise LLC changed their name to Cruise LLC in 2019.

Appendix 4

Figure 16: CA DMV Collision Reporting Form



A Public Service Agency

REPORT OF TRAFFIC COLLISION INVOLVING AN AUTONOMOUS VEHICLE

DMV USE ONLY

AVT NUMBER

NAME

Instructions: Please print within the spaces and boxes on this form. If you need to provide additional information on a separate piece of paper(s) or you include a copy of any law enforcement agency report, please check the box to indicate "Additional Information Attached."

- Write **unk (for unknown)** or **none** in any space or box when you do not have the information on the other party involved.
- Give insurance information that is complete and which correctly and *fully* identifies the **company** that issued the insurance policy or surety bond, or whether there is a certificate of self-insurance.
- Place the National Association of Insurance Commissioners (NAIC) number for your Insurance or Surety Company in the boxes provided. The NAIC number should be located on the proof of insurance provided by you company or you can contact your insurer for that information.
- Identify any person involved in the accident (driver, passenger, bicyclist, pedestrian, etc) that you saw was injured *or* complained of bodily injury or know to be deceased.
- Record in the PROPERTY DAMAGE line any damage to telephone poles, fences, street signs, guard post, trees, livestock, dogs, buildings, parked vehicles, etc., including a description of the damage.
- Once you have completed this report, please mail to: Department of Motor Vehicles, Occupational Licensing Branch, P.O. Box 932342, MS: L224, Sacramento, CA 94232-3420

SECTION 1 — MANUFACTURER'S INFORMATION

MANUFACTURER'S NAME | AVT NUMBER

BUSINESS NAME | TELEPHONE NUMBER ( )

STREET ADDRESS | CITY | STATE | ZIP CODE

SECTION 2 — ACCIDENT INFORMATION/VEHICLE 1

DATE OF ACCIDENT | TIME OF ACCIDENT ☐ AM ☐ PM | VEHICLE YEAR | MAKE | MODEL

LICENSE PLATE NUMBER | VEHICLE IDENTIFICATION NUMBER | STATE VEHICLE IS REGISTERED IN

ADDRESS/LOCATION OF ACCIDENT | CITY | COUNTY | STATE | ZIP CODE

Vehicle was: ☐ Moving ☐ Stopped in Traffic **Involved in the Accident:** ☐ Pedestrian ☐ Bicyclist ☐ Other _____ | NUMBER OF VEHICLES INVOLVED

DRIVER'S FULL NAME (FIRST, MIDDLE, LAST) | DRIVER LICENSE NUMBER | STATE | DATE OF BIRTH

INSURANCE COMPANY NAME OR SURETY COMPANY AT TIME OF ACCIDENT | POLICY NUMBER

COMPANY NAIC NUMBER | POLICY PERIOD FROM _____ TO _____

Describe Vehicle Damage

☐ UNK ☐ NONE ☐ MINOR ☐ MOD ☐ MAJOR

Shade in Damaged Area

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SECTION 3 — OTHER PARTY'S INFORMATION/VEHICLE 2

VEHICLE YEAR | MODEL

LICENSE PLATE NUMBER | VEHICLE IDENTIFICATION NUMBER | STATE VEHICLE IS REGISTERED IN

Vehicle was: ☐ Moving ☐ Stopped in Traffic **Involved in the Accident:** ☐ Pedestrian ☐ Bicyclist ☐ Other _____ | NUMBER OF VEHICLES INVOLVED

DRIVER'S FULL NAME (FIRST, MIDDLE, LAST) | DRIVER LICENSE NUMBER | STATE | DATE OF BIRTH

INSURANCE COMPANY NAME OR SURETY COMPANY AT TIME OF ACCIDENT | POLICY NUMBER

COMPANY NAIC NUMBER | POLICY PERIOD FROM _____ TO _____

☐ **Additional information attached.**

SECTION 4 — INJURY/DEATH, PROPERTY DAMAGE

NAME (FIRST, MIDDLE, LAST)

ADDRESS | CITY | STATE | ZIP CODE

CHECK ALL THAT APPLY ☐ Injured ☐ Deceased ☐ Driver ☐ Passenger ☐ Bicyclist ☐ Property

NAME (FIRST, MIDDLE, LAST)

ADDRESS | CITY | STATE | ZIP CODE

CHECK ALL THAT APPLY ☐ Injured ☐ Deceased ☐ Driver ☐ Passenger ☐ Bicyclist ☐ Property

PROPERTY DAMAGE

PROPERTY OWNER'S NAME | TELEPHONE NUMBER ( )

STREET ADDRESS | CITY | STATE | ZIP CODE

WITNESS NAME | TELEPHONE NUMBER ( )

STREET ADDRESS | CITY | STATE | ZIP CODE

WITNESS NAME | TELEPHONE NUMBER ( )

STREET ADDRESS | CITY | STATE | ZIP CODE

☐ **Additional information attached.**

SECTION 5 — ACCIDENT DETAILS - DESCRIPTION

☐ Autonomous Mode ☐ Conventional Mode

☐ **Additional information attached.**

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ITEMS MARKED BELOW FOLLOWED BY AN ASTERISK (*) SHOULD BE EXPLAINED IN THE NARRATIVE

	WEATHER (MARK 1 to 2 ITEMS)	VEH 1	VEH 2	MOVEMENT PRECEDING COLLISION	VEH 1	VEH 2	OTHER ASSOCIATED FACTOR(s) (MARK ALL APPLICABLE)
	A. CLEAR			A. STOPPED			A. CVC SECTIONS VIOLATED
	B. CLOUDY			B. PROCEEDING STRAIGHT			CITED ☐ YES ☐ NO
	C. RAINING			C. RAN OFF ROAD			
	D. SNOWING			D. MAKING RIGHT TURN			
	E. FOG/VISIBILITY			E. MAKING LEFT TURN			
	F. OTHER			F. MAKING U TURN			B. VISION OBSCUREMENT ☐
	G. WIND			G. BACKING			C. INATTENTION* ☐
	LIGHTING			H. SLOWING/STOPPING			D. STOP & GO TRAFFIC ☐
	A. DAYLIGHT			I. PASSING OTHER VEHICLE			E. ENTERING/LEAVING RAMP ☐
	B. DUSK – DAWN			J. CHANGING LANES			F. PREVIOUS COLLISION ☐
	C. DARK –STREET LIGHTS			K. PARKING MANUEVER			G. UNFAMILIAR WITH ROAD ☐
	D. DARK – NO STREET LIGHTS			L. ENTERING TRAFFIC			H. DEFECTIVE VEH EQUIP CITED ☐ YES ☐ NO
	E. DARK –STREET LIGHTS NOT FUNCTIONING*			M. OTHER UNSAFE TURNING			
	ROADWAY SURFACE			N. XING INTO OPPOSING LANE			
	A. DRY			O. PARKED			I. UNINVOLVED VEHICLE ☐
	B. WET			P. MERGING			J. OTHER* ☐
	C. SNOWY – ICY			Q. TRAVELING WRONG WAY			K. NONE APPARENT ☐
	D. SLIPPERY (MUDDY, OILY, ETC.)			R. OTHER*			L. RUNAWAY VEHICLE ☐
	ROADWAY CONDITIONS (MARK 1 TO 2 ITEMS)			**TYPE OF COLLISION**			
	A. HOLES, DEEP RUT*			A. HEAD-ON			
	B. LOOSE MATERIAL ON ROADWAY			B. SIDE SWIPE			
	C. OBSTRUCTION ON ROADWAY*			C. REAR END			
	D. CONSTRUCTION – REPAIR ZONE			D. BROADSIDE			
	E. REDUCED ROADWAY WIDTH			E. HIT OBJECT			
	F. FLOODED*			F. OVERTURNED			
	G. OTHER*			G. VEHICLE/PEDESTRIAN			
	H. NO UNUSUAL CONDITIONS			H. OTHER*			

SECTION 6 — CERTIFICATION

I certify (or declare) under penalty of perjury under the laws of the State of California that the foregoing is true and correct.

I further certify that I am the authorized Administrator of the program for the above named employer.

PROGRAM DIRECTOR/AUTHORIZED REPRESENTATIVE PRINTED NAME AND TITLE | TELEPHONE NUMBER ( )

SIGNATURE X | DATE SIGNED

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Appendix 5

Figure 17: ADS Collision Types Source: CA DMV Collision Reports 2014-April 14, 2019			
Collision Type	Autonomous mode collisions	Conventional mode collisions	Total collisions
rear end	68	23	91
side swipe	20	14	34
other	3	5	8
hit object	1	5	6
broadside	1	5	6
vehicle pedestrian	1	0	1
head on	0	6	6
Total	94	58	152

Appendix 6

Figure 18: ADS Collision Damage Types Source: CA DMV Collision Reports 2014-April 14, 2019			
Damage type	Autonomous mode collisions	Conventional mode collisions	Total collisions
major	2	2	4
moderate	13	10	23
minor	73	44	117
none	6	2	8
Total	94	58	152

the PaulDouglas institute

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