Analyzing Autonomous Car Crashes in California

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ABSTRACT
While twelve states explicitly allow autonomous vehicles (AVs) to be tested on their public roads, California still remains a pivotal location in the United States to test and study AVs. Testing is only likely to increase because in 2018 the state’s Department of Motor Vehicles changed its regulations to allow AVs to drive on public roads without humans present. This report builds on prior research to analyze the AV accident reports produced by seven companies from September 2014 through May 2018. The crashes were analyzed through six different lenses: accident frequency, speed, relative velocity, crash type, vehicular damage, and injuries. The data shows both the possible strengths and weaknesses of self-driving cars and suggests areas where improvement can be achieved, both in AV performance and transparency. Lastly, the report provides a brief analysis of the varying state laws that apply to AVs.

INTRODUCTION
Prior to 2017, autonomous vehicle (AV) testing in California was dominated by Waymo, the self-driving affiliate of Google. Moreover, the California DMV required a human operator be in the AV at all times during testing. Now General Motors (GM) has increased its testing significantly, a combined over 1.6 million miles have been logged on public roads in California, and the state changed its regulations in 2018 to allow driverless testing. That means companies like Waymo, which have been testing fully autonomous cars in other states, will eventually be doing the same in California. Meanwhile, Google Trends data illustrates that the public’s interest in autonomous cars has steadily increased since the first California DMV’s first crash report was published in 2014. Consequently, it is an appropriate time to analyze the performance of AVs in California.
Previous research analyzed the first 26 crashes that occurred from September 2014 through March 2017. Since then, however, there have been 40 more crashes in little more than a year. This increased frequency of crashes represents the greater degree of testing in the state, largely buoyed by the presence of GM. This report analyzes all 66 crashes and breaks down the analysis into seven sections:

- Accident Frequency
- Speed
- Relative Velocity
- Crash Type
- Vehicular Damage
- Injuries
- Legislation

The last section on legislation focuses on state laws and illustrates which states allow AV testing and to what degree.

The California DMV requires all companies testing autonomous vehicles in the state to fill out a report each time a crash occurs and provide a year-end report that lists all the times autonomous technology was disengaged during testing. The former includes detailed descriptions of the accidents, while the latter refers to times a human operator took control of the AVs’ operations. One of the accomplishments of this report is converting the DMV reports into a database that is publicly available for other researchers and journalists here. The Google Sheet can be filtered numerous ways, including by accident date, vehicular damage, crash type, and if injuries occurred. In addition, the detailed accident description from the reports provided to the DMV are listed as well.

For the purposes of this report, an autonomous vehicle can be considered as either semi-autonomous or fully autonomous. The Society of Automotive Engineers (SAE) categorizes autonomous driving in six levels. The first level is zero, which is no automation. Levels 1 through 3 are considered semi-autonomous because human drivers are fallbacks in case the autonomous technology (AT) experiences a failure. Levels 4 and 5 are considered restricted full autonomy and unrestricted full autonomy, respectively. The difference depends on the driving conditions and modes the AV can handle. To see a more detailed analysis, see “Examining Accident Reports Involving Autonomous Vehicles in California.” Lastly, this report often uses the more well-known names of companies to make reading easier for the audience. Consequently, GM Cruise is often referred to as GM and Waymo, formerly the Google self-driving car project and child company of Alphabet, Inc., is referred to as Google.

The first objective of this report was to compare AV accident frequencies to convention vehicles.

**ACCIDENT FREQUENCY**

One of the main concerns about autonomous vehicles is their safety. Recent polling of over 2,000 U.S. citizens revealed that 50 percent of respondents believed self-driving vehicles were less safe than human drivers. It is also probably not a coincidence that internet users searched “autonomous cars” more in March 2018—the month an Uber AV struck and killed a pedestrian in Arizona—than any other month in history. Since the California DMV began requiring manufacturers to report accidents, miles driven, and disengagements in 2014, autonomous vehicles have driven over 1.6 million miles on public roads in
One way we examined the safety of autonomous vehicles is through their miles per accident ratio.

Compared to the national crash rates for conventional vehicles, autonomous cars have been involved in more crashes per mile. According to the 2015 NHTSA data, there was one accident for every 492,000 miles driven by a conventional vehicle in 2015. Meanwhile, autonomous vehicles have been in one accident for every 31,000 miles driven through 2017. There are several caveats to this preliminary statistic though.

First, this statistic includes crashes where human operators were driving the AV. Consequently, the vehicles were not in autonomous mode. A more accurate representation of the accident rate is what we call the adjusted crash rate. It is an accident rate for autonomous vehicles that excludes instances where autonomous mode was disengaged unless the disengagement occurred immediately before the crash because the human operator felt autonomous mode would fail to handle the situation properly. There were 11 such instances in our database, and ten of them happen prior to 2018. When the ten accidents are excluded, the miles per accident ratio for autonomous cars is slightly over 36,000 miles per accident through 2017. While we know about the crashes that have occurred in 2018 so far, testing companies report their miles driven at the end of the calendar year. Thus, we cannot calculate the miles per accident for 2018 yet.

Second, the sample size is small. It would take years of continuous driving by autonomous vehicles to produce even a reliable rate. At the beginning of 2018, only five organizations had autonomous operations that passed the 10,000-mile mark on public roads in California. Consequently, a single accident can greatly skew the ratio. Second, the crash rate varies significantly by manufacturer. For example, Google’s autonomous vehicles, both Google and Waymo registered vehicles, have an adjusted accident to mile ratio of 59,000 to 1.

Third, the NHTSA data only includes police-reported crashes. The absence of non-police-reported crashes means that there are likely more accidents occurring than being reported. In addition, our accident database includes accidents that may go unreported if they did not involve AVs. For example, one accident occurred when a GM Cruise was operating in conventional mode and stopped at an intersection in 2018. A taxi driver in front of the AV left his vehicle and slapped the GM Cruise, which was reported as an accident to the DMV. In a 2015 survey of over 2,000 participants, the NHTSA found that about 29 percent of crashes go unreported. If the number of overall vehicle crashes in the U.S. is increased by 29 percent, the new miles to accident ratio is 381,000 to 1.

Lastly, the increased adoption of assisted technology may also be improving the crash rate. As this report later discusses, autonomous cars appear adept at avoiding rear ending other vehicles. Assisted driving technology, which is available in many commercially sold vehicles, incorporates functions such as automatic forward breaking that can help avoid a crash or lower the speed at impact.

Figure 1 lists the miles per accident ratios for AVs and compares them to conventional vehicles.
Figure 1: Conventional and Adjusted Autonomous Accident Frequencies Compared Through 2017

<table>
<thead>
<tr>
<th>Type</th>
<th>Total Miles</th>
<th>Total Number of Accidents</th>
<th>Miles per Accident</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conventional Vehicles</td>
<td>3.095 Trillion</td>
<td>6,296,000</td>
<td>491641</td>
</tr>
<tr>
<td>Conventional Vehicles + Unreported Est. ¹⁰</td>
<td>3.095 Trillion</td>
<td>8121840</td>
<td>381117</td>
</tr>
<tr>
<td>Autonomous Vehicles</td>
<td>1,623,867</td>
<td>52</td>
<td>31,228</td>
</tr>
<tr>
<td>Google AVs</td>
<td>1,412,744</td>
<td>23</td>
<td>54,336</td>
</tr>
<tr>
<td>GM Cruise AVs</td>
<td>141,688</td>
<td>21</td>
<td>5,550</td>
</tr>
</tbody>
</table>

With advances in technology and increased testing, one might expect the crash rate to diminish overtime. Experts have even argued that autonomous technology can learn quickly from its mistakes, unlike human drivers.¹⁴ Yet AVs were more than twice as likely to crash in 2017 compared to both 2015 and 2016. Figure 2 illustrates the miles per accident ratio for each year.

Figure 2: Combined AV Miles Per Accident From 2015-2017

A close examination of the data offers possible reasons why the overall accident rate did not improve. Until 2017, Google autonomous vehicles had driven nearly 95 percent of the total miles logged on public roads and sustained more than three-fourths of the crashes. Nonetheless, of any vehicle type that has sustained at least one crash, Google autonomous vehicles were the least likely to sustain an accident on a per mile basis.
In 2017, however, 12 manufacturers tested 198 autonomous vehicles. These vehicles drove 507,271.28 miles in the state. While over 95 percent of these miles were driven by Google or GM Cruise owned vehicles, which is why many of the charts in this report group the other ten manufacturers as an “other,” one-fourth of the autonomous miles in the state were logged by GM Cruise vehicles. Comparing the adjusted crash rates for 2017 shows that Google vehicles crashed every 118,000 miles on average while GM Cruise vehicles crashed once per every 7,000 miles. This highlights that Google may be significantly farther along in developing AV technology compared to other organizations testing in the state. Such a conclusion is compatible with Google’s lead in the number of total miles logged.

One of the main conclusions of previous research was that the number of accidents and autonomous miles travelled were highly correlated.¹⁵ A decline, or plateau, in the correlation might suggest that the autonomous technology was improving though. In particular, it could illustrate that the machine learning algorithms that power the cars had learned to successfully navigate more scenarios. Consequently, we performed the correlation analysis solely on Google. We found that increased miles and accidents are still highly correlated, but the correlation has decreased. This report broke down the correlation in 5 month increments and found that the highest correlation (.99) was for April 2015 through August 2015. The lowest correlation (.66) in five months increments was for July 2017 through November 2017, which is the most recent period we could calculate. In addition, breaking down the crashes into mileage groups revealed a decreasing crash rate. Figure 3 breaks down Google’s number of accidents in 250,000-mile increments.

*Figure 3: Google Accidents Broken Down in 250,000 Mile Increment*
**Speed**

Speeding caused more than one-fourth of all traffic fatalities in the U.S. in 2016. Consequently, we examined the speeds of autonomous vehicles at the time of the accidents. The speed of the AV was listed at 0 MPH in our database anytime the accident description stated the vehicle was stopped at the time of impact. The average speed of the autonomous vehicles was less than four MPH while the average speed for other vehicles involved in the crash was nearly 10 MPH. When examining the adjusted crash count (55 accidents), the speed the of the AV was reported 33 times. Of these accidents, we found that the AV was stopped during the majority of accidents. In addition, the AV was traveling 5 MPH or less during 84 percent of crashes. The fastest speed at the time of an accident by an AV was 22 MPH.

It is difficult to compare accident speed trends between Google and GM. Google listed the speed of the AV for all but two accidents and the data shows that half of the accidents occurred when the vehicle’s speed was 0 MPH. This includes times in which the AV braked and was rear ended. Meanwhile, GM does not indicate AV speed for 20 of its 29 accidents in which the car was in autonomous mode or recently disengaged (GM reported the speed of the AV 4 of 5 times when the crash occurred during a trip the AV was in conventional mode). Nonetheless, 4 of its 9 autonomous adjusted crashes occurred when the AV’s speed was 0 MPH.

Figure 6 illustrates the speed ranges of the AV in 5 MPH increments.

**Figure 6: Speed of Vehicles at Moment of Accident**

**RELATIVE VELOCITY**

Another way to assess the severity of accidents is through relative velocity, which is typically the difference between the speeds of vehicles involved in a crash traveling the same direction. The difference is an absolute value, and the calculation allowed us to develop a better understanding of how frequently autonomous vehicles were involved in high impact crashes. For example, a Mercedes ML350 rear ended
a Chevy Bolt AV on March 22, 2017. At the time of the collision (ID#40), the Mercedes was traveling 4 MPH and the AV was traveling 2 MPH. Consequently, the impact speed was 2 MPH. When objects are traveling in opposite directions, the speeds are summed. If an object is stationary, then the relative velocity is the speed of the impacting vehicle. One such example occurred on January 8, 2016. A GM Cruise autonomous vehicle, in which the driver had manually disengaged from autonomous mode but “did not change the path of the vehicle,” sideswiped a parallel parked Toyota Prius at 20 MPH. Consequently, the relative velocity at impact was 20 MPH. This crash represents the highest known relative velocity of an autonomous vehicle hitting a stationary object in California.

The majority of crashes examined in this report were incidents where the autonomous vehicle was rear ended though. One could expect a high relative velocity when autonomous cars abruptly break and provide little warning, and thus little time, to cars following them to break. We found that most crashes had relative speeds of 5 MPH or less. These crashes represent low impact collisions. When the crashes are isolated to only include times when the AV was rear ended, 14 of 19 collisions had a relative velocity of 5 MPH or less. Not every DMV report listed the speed of both objects though. Thus, we were able to calculate the relative speed of the crash for 27 accidents, or roughly 41 percent of all crashes. Figure 4 displays the relative velocities of crashes in speed ranges.

Figure 4: Relative Speed Range of Vehicles at Moment of Impact
Figure 5 illustrates the relative velocity of crashes overtime, where ID #1 is the most recent crash.

**Figure 5: Relative Speed of Vehicles at Moment of Accident**

Lastly, the AV was stopped in 23 of the 66 studied crashes. This statistic may suggest that many of the accidents are not the fault of the autonomous vehicle, but it is difficult to confidently make conclusions because of the reporting of the speed of vehicles at the time of collisions has been reported less and less over time. Only 5 of the last 37 accidents have reported the speed of each vehicle at the time of the crash. Yet of the first 30 crashes, both speeds were reported 22 times. While sometimes it may be impossible to accurately report the speed of the non-autonomous vehicles (such as during a hit and run), it is surprising that such basic information, which can highlight the types of crashes autonomous vehicles are engaging in, has failed to be listed on the DMV reports. We found that Google reported both speeds over 80 percent of the time. Meanwhile, GM reported both speeds 15 percent of the time. While testing companies are not required to report the speed of vehicles on the DMV reports, the NHTSA notes that abundant and accurate traffic data is critical to identify safety issues and develop solutions. Thus, reporting the speeds would increase accountability and allow for more detailed research.

**CRASH TYPES**

Another way to categorize crashes is by type. The types of crashes can reveal areas where AVs are struggling and accident types that they are successfully avoiding. This report classified crashes as either rear end, broadside (t-bone), sideswipe, or head-on collisions as well as incidents in which a stationary object was struck. A previous study, which analyzed the first 26 crashes involving autonomous vehicles in California, found that 62 percent of collisions were rear ends. An analysis including the additional forty crashes since the aforementioned report reveals that 56 percent of AV crashes in California are rear ends. This figure is still significantly higher than the roughly 30 percent of crashes involving conventional
vehicles being rear ends. Several of the accidents occurred when the AV was in conventional mode, however. When the accidents are isolated to only include instances in which autonomous mode was engaged or manually disengaged just before the moment of impact, 62 percent of the crashes were rear ends. Figure 7 breaks down the crashes by type.

**Figure 7: Number Accidents Per Crash Type**

The prevalence of rear ends supports the view that avoiding such accidents should be a top priority for autonomous manufacturers. The task may be difficult though. The crashes analyzed in this study represent both instances where an AV failed to avoid an accident, but also incidents where human operators failed to disengage autonomous mode to avoid a crash. It should also be noted that three of the rear ends were situations in which the AV had been stopped for nine seconds or more. In such scenarios, it is unlikely a failure of autonomous technology led to the crash. Despite a possible struggle to avoid being rear ended, autonomous vehicles have done well to not rear end other vehicles.

Of all the rear ends in the database, only one time did the autonomous vehicle rear end another vehicle. Moreover, autonomous mode was disengaged during the trip. Consequently, the accident was likely the fault of the human operator. This report agrees with the conclusion of previous researchers that autonomous technology was effective at avoiding collisions where it rear ended another vehicle because autonomous vehicle testing on public roads has yet to lead to a single such collision.
Besides rear ends, the most common crash type was sideswipes. Such collisions represent 20 percent of all crashes where autonomous mode was engaged or was recently disengaged.

**INJURIES**

Another area we examined was injuries. Organizations and researchers also classify accidents by the severity of injury.\(^2\) For this report, however, there was not enough information listed on the DMV reports to accurately label the severity of injuries. Nonetheless, we were able to collect statistics on how often injuries occurred and we list the descriptions of the injuries below. Often, no injuries were reported at the scene but individuals later expressed bodily discomfort and/or sought medical attention. We categorized both as injuries. If an individual did report discomfort or suffered some physical harm, even if it was scrapes, we counted it as an injury.

Less than 14 percent of the accidents resulted in injuries and a total of 14 individuals were injured. The NHTSA reports that there were 6,296,000 traffic accidents in 2015. Those accidents resulted in 2,443,000 injured people. Consequently, the accident to injury ratio for conventional vehicles is 2.58 to 1, compared to 5.50 for autonomous vehicles. Once again though, it is perhaps more accurate to only consider accidents when autonomous technology was engaged, or recently disengaged before the accident. When only such accidents are considered, the ratio for autonomous cars is slightly higher at 5.91 accidents to injured person. This could be partially a result of the low speed of many of the crashes.  

It should also be noted that while there have been no fatalities in California, an Uber autonomous vehicle struck and killed a pedestrian in Arizona in 2018.\(^3\) In that instance, the AV noticed the pedestrian six seconds before it hit her, but did not decide to engage emergency breaking until one second before impact.\(^4\) In addition, a Tesla was using autopilot when it struck a median in California, fatally killing the human driver. The autopilot function is semi-autonomous driving. It autonomously stays in its lane and maintains a distance from the vehicle ahead of it. But it also requires constant human attention and the driver needs to have their hands on the wheel at all times.\(^5\) Figure 8 lists the descriptions of each injury sustained in the autonomous car crash database when autonomous mode was engaged or recently disengaged.

![Figure 8: Injury Descriptions](image)

<table>
<thead>
<tr>
<th>Accident ID</th>
<th>Mode</th>
<th>Injury Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>Autonomous</td>
<td>Scraped legs</td>
</tr>
<tr>
<td>4</td>
<td>Autonomous</td>
<td>Stiff neck</td>
</tr>
<tr>
<td>12</td>
<td>Manually Disengaged</td>
<td>Injury box checked but no description was provided</td>
</tr>
<tr>
<td>15</td>
<td>Autonomous</td>
<td>Shoulder pain, sued GM and settled a lawsuit(^6)</td>
</tr>
<tr>
<td>22</td>
<td>Autonomous</td>
<td>Shoulder stiffness</td>
</tr>
<tr>
<td>32</td>
<td>Manually Disengaged</td>
<td>Wrist discomfort</td>
</tr>
<tr>
<td>36</td>
<td>Autonomous</td>
<td>Scraped knee</td>
</tr>
<tr>
<td>41</td>
<td>Autonomous</td>
<td>Sore knee</td>
</tr>
<tr>
<td>59</td>
<td>Autonomous</td>
<td>Three individuals complained of whiplash, one other reported minor back and neck pain</td>
</tr>
</tbody>
</table>
Figure 9 illustrates how many accidents resulted in an injury compared to those that did not.

**Figure 9: Accidents Resulting in Injuries**

<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>Count</th>
</tr>
</thead>
<tbody>
<tr>
<td>GM</td>
<td>35</td>
</tr>
<tr>
<td>Google</td>
<td>25</td>
</tr>
<tr>
<td>Other</td>
<td>5</td>
</tr>
</tbody>
</table>

**CAR DAMAGE**

Lastly, we analyzed the crashes by damage to the vehicles. Many of the reports described vehicle damage in terms such as minor, moderate, or significant. When the report stated the damage was minor or moderate, we also labeled it minor or moderate. If the report stated the damage was significant, we labeled it severe. In addition, there were reports that described vehicular damage but not did classify its severity. In such instances, we used the classifications below:

- **Minor:** Scratches, dents, scuffs, small cracks, deflated tires
- **Moderate:** Large dents, doors that will not open, etc.
- **Severe:** Broken axles, twisted frames, etc.

There were also 13 accidents in which the DMV report did not describe the accident or did indicate if there was damage. Consequently, the damage severity of those accidents are not classified in this report.

Of the 42 crashes in which damage to the autonomous vehicle is classified and the car was not in conventional mode, we found that only two crashes were moderate. Only one was severe. This finding is compatible with the majority of crashes occurring at speeds less than 10 MPH. Figure 10 shows how many accidents resulted in minor, moderate, and severe damage.
LEGISLATION

Federally, the SELF Drive Act, HR 3388, has been passed by the House of Representatives and referred to the Senate Committee on Commerce, Science, and Transportation. The bill would update safety standards and expand federal preemption by preventing states from creating certain laws that would create different requirements for autonomous vehicles across states.

Thirteen states allow AVs to be driven or tested on public roads. Within this group of states, however, the legislation varies widely. For example, there has been almost no testing in New York because its law requires all testing to be done under the supervision of state police. Massachusetts only allows testing for select companies in certain parts of Boston. Then there are states which have less restrictive laws that allow autonomous vehicles in the state.

At least eight states do not require individuals to be in the autonomous car while it is driving. This includes states such as California, which passed legislation in 2018, Michigan, and Arizona. Unlike states such as California, however, states such as Florida do not require companies to obtain a permit to test cars without a human driver in them. Lastly, Florida allows self-driving cars on public roads and it does not need to be for testing purposes. Consequently, self-driving cars can be driven in the state as a mode of transportation.
Several maps have been created that illustrate which states have passed legislation about autonomous driving and are considering it. Many of the laws are not related to actual testing of the vehicles though. Several of them allow for the creation of studies, and the most common type of legislation was for removing safe-driving distance barriers for platoons of autonomous vehicles. The map in Figure 11 though excludes states which have passed legislation about autonomous vehicles but do not allow their testing.

**Figure 11: Level of Self-Driving Allowed by State**

CONCLUSION

When compared to prior research, this report demonstrates the advances in reducing accident frequencies Google has made in the past 18 months. The report also shows, however, that autonomous vehicles are still involved in accidents more often on a per mile basis than conventional vehicles. Despite the higher accident rate, AV collisions were typically minor, in terms of speed, property damage, and injuries.

We found that rear ends have been consistently been the most frequent type of collision—62 percent of all accidents in which the AV was in autonomous mode or had recently disengaged from it. More than half of the accidents (in which the speed the AV was reported) occurred when the AV was stopped. This finding was compatible with our analysis of the relative velocity of the crashes, 63 percent occurred at 5
MPH or less. In addition, 93 percent of the crashes resulted in minor or damage. Lastly, we also found a disappointing trend that vehicular speeds at the time of impact were being reported less. It is our hope that revealing this will lead to the speeds being reported, which can help future research.

Each conclusion of this report is only preliminary, however. There are significant limits because of the small dataset of only 66 crashes and less than two million total miles logged in California. Future research can leverage the publicly available database we created and continue to track the trends identified in this report.

REFERENCES


3. Favarò et al.


5. Favarò et al.


7. “Autonomous Cars.”


10. We cannot make this calculation through 2018 because manufacturers submit their reports on miles driven and disengagements to the DMV at the end of the calendar year.


13. This figure is the total number of accidents by conventional figures multiplied by 1.29 to account for the estimated number of crashes that go unreported to police.

15. Favarò et al.


18. Favarò et al.


