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16. Abstract

This study performed a preliminary analysis of the cumulative on-road safety record of self-driving vehicles for three of the ten companies that are currently approved for such vehicle testing in California (Google, Delphi, and Audi). The analysis compared the safety record of these vehicles with the safety record of all conventional vehicles in the U.S. for 2013 (adjusted for underreporting of crashes that do not involve a fatality).

Two important caveats should be considered when interpreting the findings. First, the distance accumulated by self-driving vehicles is still relatively low (about 1.2 million miles, compared with about 3 trillion annual miles in the U.S. by conventional vehicles). Second, self-driving vehicles were thus far driven only in limited (and generally less demanding) conditions (e.g., avoiding snowy areas). Therefore, their exposure has not yet been representative of the exposure for conventional vehicles.

With these caveats in mind, there were four main findings. First, the current best estimate is that self-driving vehicles have a higher crash rate per million miles traveled than conventional vehicles, and similar patterns were evident for injuries per million miles traveled and for injuries per crash. Second, the corresponding 95% confidence intervals overlap. Therefore, we currently cannot rule out, with a reasonable level of confidence, the possibility that the actual rates for self-driving vehicles are lower than for conventional vehicles. Third, self-driving vehicles were not at fault in any crashes they were involved in. Fourth, the overall severity of crash-related injuries involving self-driving vehicles has been lower than for conventional vehicles.

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Contents

Introduction

Self-driving or autonomous vehicles are expected to deliver several key advantages over traditional, human-driven vehicles. The potential benefits include increased mobility and travel convenience, decreased congestion and reduced travel times, and improvements in safety for all traffic participants. While the effects on mobility and congestion are still speculative until large numbers of self-driving vehicles take to the roads, the ability to analyze the real-world safety aspects is starting to become possible. Though still in what many would consider their infancy, self-driving vehicles have collectively accrued over 1 million miles on public roads (though under somewhat limited circumstances and in specific environments or locations) (Audi, 2015b; Delphi, 2015; Google, 2015). (In this report, the terms "self-driving vehicle" and "autonomous vehicle" have the same meaning; "autonomous mode" refers to the fully automated operation of a self-driving vehicle.)

Several U.S. states have passed legislation allowing the operation and/or testing of self-driving vehicles on public roads, including California (NCSL, 2015). Currently, several manufacturers are operating and testing self-driving vehicles on public roads in California, which has specific regulations regarding the operation and testing of self-driving vehicles (referred to in the regulations as "autonomous vehicles"; State of California, 2015a). These requirements include the duty to submit specific information, such as detailed company, vehicle fleet, operator, and training information to obtain a permit for testing (form OL 311), evidence of insurance specific to testing self-driving vehicles (form OL 317), and documentation of *any* crashes involving such vehicles in either autonomous or conventional mode (i.e., manual control) (form OL 316). A current list of approved testers is shown in Table 1.

The contents of the OL 316 crash reports (State of California, 2015b), combined with other public reporting of self-driving vehicle crashes (Google, 2015), formed the basis of the self-driving vehicle crash data used in this report. Due to the lack of public data regarding the driving experience of most self-driving vehicle test companies and their self-driving vehicle fleets, we will examine data for only three of the ten currently approved testing companies in this report. The general self-driving vehicle-crash trends documented in this report will be compared with analogous conventional-vehicle crash statistics for the entire U.S. (NHTSA, 2015b).

Table 1
Self-driving vehicle testing companies currently approved by the State of California (State of California, 2015a).

Approved self-driving vehicle testing company	Included in this analysis
BMW	
Bosch	
Cruise Automation	
Delphi Automotive	X
Google	X
Honda	
Mercedes Benz	
Nissan	
Tesla Motors	
Volkswagen Group of America (includes Audi)	X

Method

Crash data

Self-driving vehicle fleets

Table 2 lists the publicly disclosed on-road experience of the self-driving vehicles included in this analysis. The self-driving vehicle fleets currently (or recently) driving on public roadways in the U.S. are described, including broad summaries of each company's crash and associated injury experience. Crashes occurring while a self-driving vehicle was being operated in conventional mode have been excluded from this analysis. Two of the crashes listed in the self-driving vehicle category occurred while the respective self-driving vehicle operator was attempting to transition to manual control of the vehicle (immediately preceding the crash), and therefore are listed as conventional mode in the crash reports. However, as the critical events for both crashes developed while the vehicles were in autonomous mode, and there is no indication that the outcomes would have been different if the vehicle had remained in autonomous mode, we have included those two crashes in the self-driving vehicle category.

Table 2
Publicly disclosed on-road experience of the self-driving vehicles included in this analysis (AV: autonomous vehicle mode, CV: conventional vehicle mode).

Company	Current vehicle fleet	Distances in autonomous mode and geographic range	Crashes	Total injuries
Google	23 Lexus RX450h 25 custom prototypes	~ 1.2 million miles Mostly in Mountain View, CA and some in Austin, TX	AV: 11 CV: 5	AV: 4* CV: 0
Delphi	1 Audi SQ5 ("Roadrunner")	~ 3400 miles Single trip from San Francisco to New York City	AV: 0 CV: 1**	0
Audi[1]	1 Audi A7 ("Jack")	~ 550 miles Single trip from San Francisco to Las Vegas	0	0

* These 4 injuries occurred in 2 different crashes.
** This crash did not occur during Delphi's coast-to-coast trip.

[1] Audi has operated several other self-driving vehicles, albeit in closed-road or closed-track environments (e.g., "Shelley," the Audi TTS that completed the Pikes Peak International Hill Climb [Audi, 2015a]).

Crash database coverage

The following summarizes the coverage of each crash database used in this analysis:

Conventional vehicles

The FARS (Fatality Analysis Reporting System) and GES (General Estimates System) crash statistics summarized in *Traffic Safety Facts 2013* cover all 50 states and the District of Columbia. The summaries represent crash results for approximately 269 million vehicles traveling nearly 3 trillion miles per year in the U.S. for 2013 (the latest year available) (NHTSA, 2015b).

Fatal injury statistics are derived from FARS, a *census* of all crashes involving a fatality occurring on public roads in the U.S.

Nonfatal injury statistics are derived from GES, a representative *sample* of all crash severities (from property-damage only to fatal crashes) occurring on public roads in the U.S. The GES sample (approximately 57,000 randomly selected cases) is drawn from reported crashes that result in the filing of a police report (approximately 5.7 million total police-reported crashes in 2013). Weighted GES data can be used to estimate the various types, severities, and circumstances of crashes occurring on U.S. roads.

Self-driving vehicles

We have included a *cumulative census* of all crash data relative to these vehicles, covering 2012 through September 2015. The self-driving vehicle crash data were compiled from the OL 316 forms provided to the California DMV[2] (for crashes in 2014 and 2015) and from Google's self-reported crash descriptions (for crashes prior to 2014). The geographic coverage (i.e., area of public operation) of the fleets in this analysis center mostly in and around Mountain View, California and Austin, Texas for Google; for Delphi, a single, coast-to-coast trip of approximately 3400 miles is included; for Audi, a single trip from San Francisco to Las Vegas of approximately 550 miles is included. A map illustrating the geographic coverage of these self-driving vehicle fleets is shown in Figure 1.

[2] We are unaware of any crashes involving Google's self-driving vehicle fleet in Texas. However, there is no special requirement to document and/or report self-driving vehicle crashes in Texas as exists in California. Similarly, we are unaware of any crashes involving the Delphi or Audi self-driving vehicles during any portion of their trips outside of California. As such, all documented self-driving vehicle crashes included in this analysis occurred within California.

Figure 1. Geographic coverage of the current self-driving vehicle fleets. The red dots represent the geographic areas that the Google fleet generally operates within on a daily basis, while the blue and green paths represent the approximate routes taken by Delphi and Audi, respectively, on their individual long-distance self-driving vehicle trips.

Results

Where possible and appropriate, the self-driving vehicle crash summaries will be compared against corresponding summaries of national crash results (representing conventional vehicles).

Frequency of crashes

Table 3 shows the frequency of self-driving vehicle crashes (while in autonomous mode) by year from 2012 (the year of the first known crash involving a self-driving vehicle in autonomous mode[3]) through September 2015. The frequency of crashes involving self-driving vehicles increased for the latest year, presumably corresponding to the recent increase in the number of self-driving vehicles operating on public roads. Self-driving vehicles have not been found to be at fault in any of the 11 crashes occurring in autonomous mode.

Table 3
Frequency of self-driving vehicle crashes by year, 2012 through September 2015.

Year	Number of crashes
2012	1
2013	1
2014	1
2015	8
Total	*11*

[3] Self-driving vehicles have been operating on public roads since 2009, but all reported self-driving vehicle crashes prior to 2012 involved vehicles operated in conventional mode.

Vehicle motion at the time of crash

Table 4 presents a breakdown of the self-driving vehicle motion (stopped or slow in traffic versus driving) for all recorded crashes in autonomous mode at the time of impact. The majority of self-driving vehicle crashes (73%) occurred while the vehicle was stopped or slow (≤5 mph) in traffic.

Table 4
Breakdown of self-driving vehicle motion at the time of impact.

Year	Number of crashes	Percentage of crashes
Driving (>5 mph)	3	27.3%
Stopped or slow (≤5 mph) in traffic	8	72.7%

For the following graphs of self-driving vehicle crash results, the number of crashes precedes the percentage of crashes in each label. (The estimated number of crashes is not shown for the conventional-vehicle crash results.)

Crash type – first harmful event

Figure 2 presents the proportions of crashes by general crash categories (i.e., first harmful event) for conventional vehicles and self-driving vehicles. While most conventional vehicle crashes (68%) occur with another motor vehicle, all self-driving vehicle crashes (100%) have occurred with another motor vehicle.

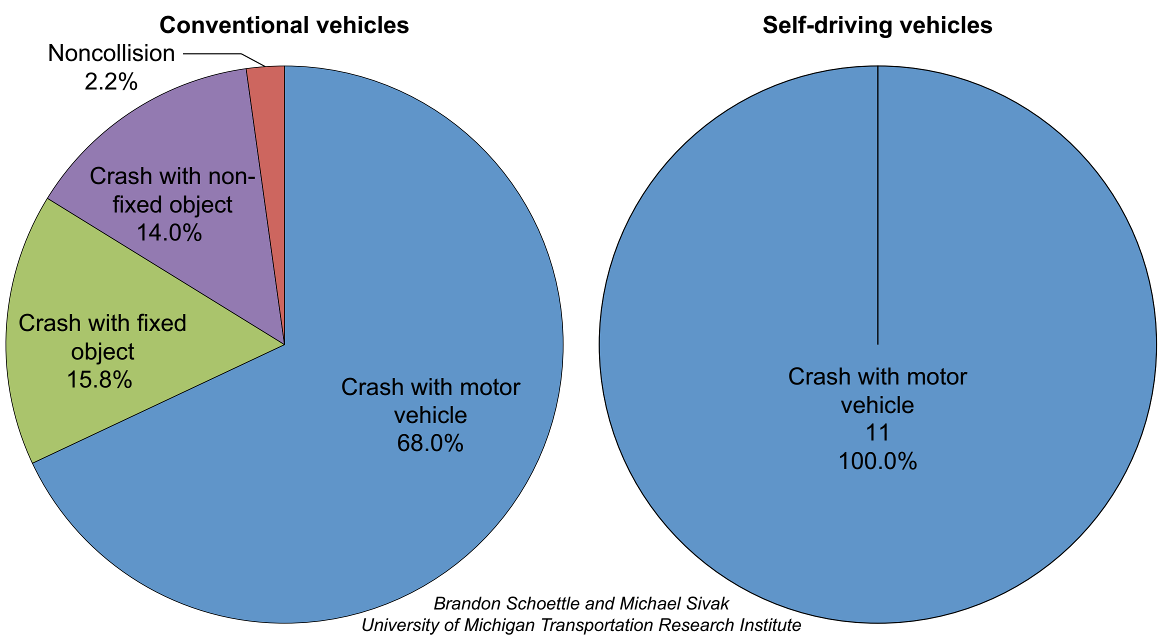

Figure 2. Percentages of crash types by first harmful event for conventional vehicles and self-driving vehicles.

Crash type – manner of collision

Figure 3 presents the proportions of crashes within the *Crash with motor vehicle* category by specific manner of collision for conventional vehicles and self-driving vehicles. Rear-end crashes were the most common collision for both vehicle types, although self-driving vehicles were rear-ended 1.5 times more often than conventional vehicles (73% versus 48%, respectively). The remaining self-driving vehicle crashes involved two sideswipes (18%) and one angle (9%). Head-on collisions, while constituting 4% of conventional vehicle crashes, have thus far been completely avoided by self-driving vehicles.

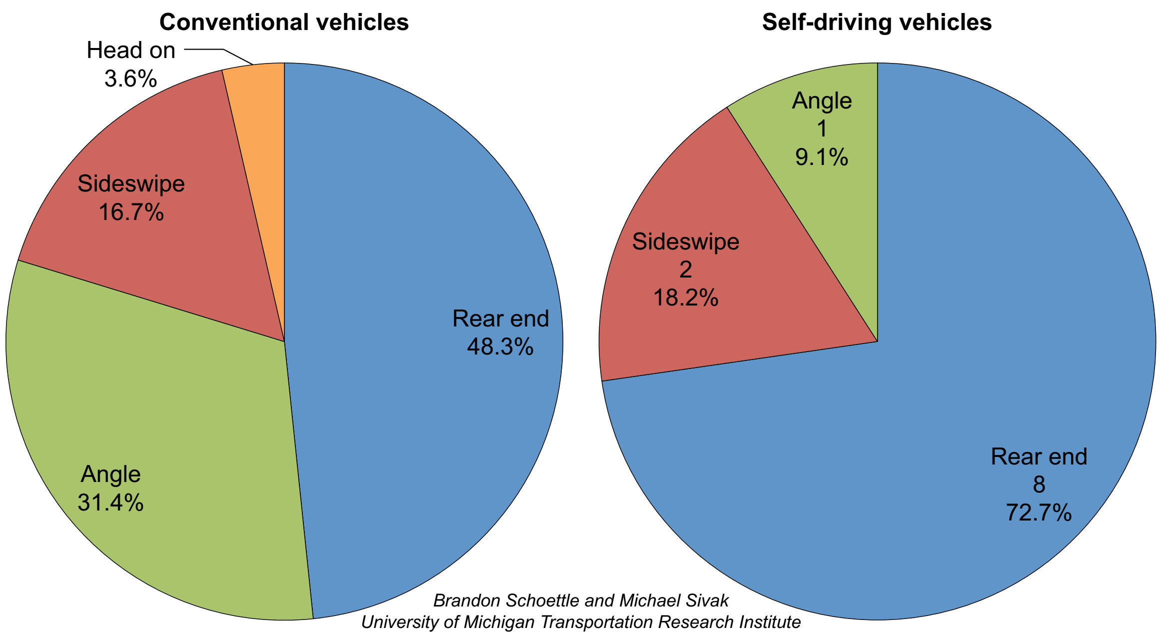

Figure 3. Percentages of crash types by manner of collision for conventional vehicles and self-driving vehicles.

Crash severity

Figure 4 shows the proportions of crashes by severity for conventional vehicles and self-driving vehicles. Property-damage-only crashes were the most common for both vehicle types, although self-driving vehicles experienced such crashes 10% more often than conventional vehicles (82% versus 72%, respectively). Correspondingly, crashes resulting in injury[4] were 10% lower for self-driving vehicles than for conventional vehicles (18% versus 28%, respectively). To date, no self-driving vehicles have been involved in any fatal crashes, compared with 0.5% of all conventional vehicle crashes. The nonfatal injury levels include (from most to least severe) *incapacitating injury*, *non-incapacitating injury*, and *possible injury*; each injury described in the self-driving vehicle crash reports would likely qualify as a *possible injury* (least severe).

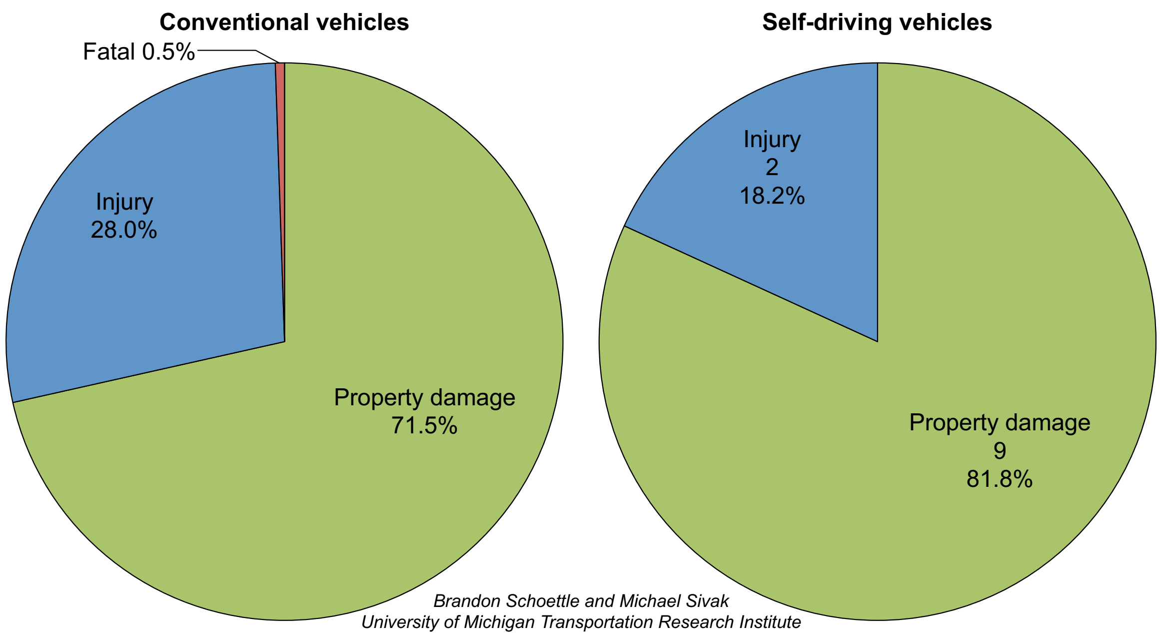

Figure 4. Percentages of crashes by crash severity for conventional vehicles and self-driving vehicles.

[4] The 4 injuries involving self-driving vehicles occurred in 2 separate crashes.

Crash and injury rates

Table 5 shows the crash and injury rates per million miles of vehicle travel for conventional vehicles and self-driving vehicles[5,6]. Currently, the overall crash rate for self-driving vehicles is nearly five times the rate for conventional vehicles. Although the injury rate is more than four times higher for self-driving vehicles than conventional vehicles (3.29 versus 0.77 per million miles, respectively), the injury severity appears to be lower than for conventional vehicles (see the previous *Crash severity* section). While the conventional vehicle fatality rate is 0.01, the rate for self-driving vehicles is currently 0 as there have been no recorded fatalities with such vehicles. The injury rate per crash is higher for conventional vehicles (0.41) than for self-driving vehicles (0.36).

Table 5
Crash and injury rates for conventional vehicles and self-driving vehicles.

Vehicle type	Rates per million vehicle miles of travel			Injuries per crash
	Crashes	Injuries (nonfatal)	Fatalities	
Conventional vehicles	1.9	0.77	0.01	0.41
Self-driving vehicles	9.1	3.29	0	0.36

[5] Self-driving vehicle injury rates were calculated based on the number of fatalities (0), the number of total injuries (4 in autonomous mode; see Table 2), the number of total crashes (11 in autonomous mode), and the total mileage documented in this report (1,214,626 miles in autonomous mode).

[6] As described in the Method section, the 11 crashes for self-driving vehicles include 9 crashes in autonomous mode and 2 crashes with the operator attempting to transition from autonomous to conventional mode at the time of the crash.

Discussion

Data limitations

Small sample size for self-driving vehicle crashes

Though impressive considering that we are still in the early stages of self-driving vehicle development, the fleet sizes and accrued mileage are fairly small, with 50 vehicles fielded by three companies accounting for just over 1.2 million miles. For comparison, as described in the Method section, the conventional vehicle data in this study are based on nearly 3 trillion annual miles accumulated by 269 million vehicles.

Furthermore, the current number of self-driving vehicle crashes stands at 11 versus 5.7 million police-reported crashes (of any type) in the U.S. in 2013. When comparing self-driving vehicle crashes to crash summaries for conventional vehicles, it is important to note that the self-driving vehicle crash data are a census of all crashes (as required by California law), while the conventional vehicle summaries are estimates based on sampling of police-reported crashes (for crashes not involving a fatality).

Coverage and exposure

While the details of the exact exposures for the current self-driving vehicle fleets have not been made public, it is a reasonable assumption that their exposure is not representative of the exposure for conventional vehicles in the U.S. For example, as described in Table 2 of this report and shown in Figure 1, the geographic coverage for the self-driving vehicle fleets in this analysis are not representative of most driving in the U.S. The areas these vehicles operate in tend to be southern states and states without inclement winter environments. Having accrued the overwhelming majority of the miles in this analysis (99%), Google operates their vehicles mainly on local roads in Mountain View, California (and very recently Austin, Texas). (All crashes for self-driving vehicles documented in this report have occurred on local roads in urban areas [Hernandez, 2015].) The publicly disclosed experiences of Delphi and Audi were generally constrained to limited-access highways on two long-distance trips, ensuring they avoided severe or winter weather (Davies, 2015; Fingas, 2015). Also, it is unclear to what extent any of these vehicles have performed nighttime driving on public roads.

Based on the brief history and relatively low mileage of self-driving vehicles on public roads, limited or complete lack of exposure to various challenging traffic scenarios and events needs to be taken into account when interpreting crash results for self-driving vehicles. For example, the absence of head-on crashes involving self-driving vehicles may be due to the ability of these vehicles to avoid such crashes, or may simply be due to having encountered such events relatively infrequently. Without more information about exposure, the overall performance of self-driving vehicles under the full range of circumstances remains uncertain.

Autonomous mode limitations

The autonomous modes of the vehicles in each fleet examined here had unique limitations. For example, the Google self-driving vehicle fleet is limited to the cities or areas for which they have developed highly detailed, three-dimensional maps. Though the reasons one might use one of their self-driving vehicles in conventional mode versus autonomous mode are not publicly disclosed (perhaps, for example, when leaving the area for which Google maintains detailed maps), Google's fleet has been used in autonomous mode for approximately 57% of the total distance driven (Google, 2015). Delphi claims to have driven in autonomous mode for 99% of their coast-to-coast trip, though this was done almost entirely on highways (Davies, 2015). Without putting a percentage on distance driven in autonomous mode, Audi acknowledges that their vehicle was only in autonomous mode on their trip when driving on highways (Fingas, 2015).

Crash circumstances

Based on narratives supplied in the crash descriptions for the crashes occurring in autonomous mode, the self-driving vehicles do not appear to be at fault in any of the crashes that have occurred to date. (Any at-fault crashes within each fleet occurred during conventional mode operation of a vehicle.) All self-driving vehicle crashes occurred with another motor vehicle. Although a majority (68%) of conventional vehicle crashes occurred with another motor vehicle, some occurred with fixed objects (16%) and non-fixed objects (14%), and a small portion were considered noncollisions (2%). Crashes involving self-driving vehicles usually occurred when the vehicles were stopped or slow in traffic, and rear-end crashes (by a conventional vehicle) were the most common type of crash scenario. Head-on crashes constitute 4% of conventional vehicle crashes, but have yet to occur with any self-driving vehicles.

Crash outcomes

The most common outcome of crashes for both vehicle types was property-damage only, but self-driving vehicles had this outcome 10% more often than conventional vehicles. Consequently, self-driving vehicles experienced injury-related crashes 10% less often than conventional vehicles. The overall severity of crashes involving self-driving vehicles was also lower than for conventional vehicles. As with the previous discussion regarding crash circumstances, these differences should be considered tentative, and could be due to different exposures between the vehicle types that we noted earlier.

Adjusted crash rates, injury rates, and confidence intervals

Because approximately 60% of property-damage-only crashes and 24% of injury crashes go unreported each year (NHTSA, 2015a), we have calculated adjustments to the crash and injury rates of conventional vehicles to account for this underreporting (by using factors of 2.5 and 1.32, respectively, to multiply the original GES estimates for these crash types); no adjustments were made to the self-driving vehicle rates.

Furthermore, to account for the fact that (1) the GES data represent a probability sample and (2) only a relatively small number of self-driving vehicles have been publicly tested, we have calculated 95% confidence intervals for the results for both vehicle types. The confidence intervals for the GES data were derived from the technical notes in Appendix C of *Traffic Safety Facts 2013* (NHTSA, 2015b), while those for self-driving vehicles were calculated using Poisson-distribution confidence intervals for samples with a small number of events (Schoenberg, 1983). (Poisson-distribution confidence intervals are generally asymmetrical with a positive skew [Bissell, 1994]. Confidence intervals for normally distributed data, such as GES, are symmetrical.)

Table 6 shows the adjusted crash and injury rates for conventional vehicles that account for the underreporting of property-damage-only and injury crashes (and related injuries[7]), and the 95% confidence intervals for both vehicle types (in parentheses). The results are presented graphically in Figure 5.

Table 6
Adjusted crash and injury rates (with 95% confidence intervals in parentheses) for conventional vehicles and self-driving vehicles.

Vehicle type	Crashes per million vehicle miles traveled		Injuries per million vehicle miles traveled		Injuries per crash	
	Original	**Adjusted**	Original	**Adjusted**	Original	**Adjusted**
Conventional vehicles	1.9	**4.1 (3.5 - 4.7)**	0.77	**1.02 (0.88 - 1.16)**	0.41	**0.25 (0.19 - 0.33)**
Self-driving vehicles	9.1	**9.1 (4.5 - 16.3)**	3.29	**3.29 (0.90 - 8.42)**	0.36	**0.36 (0.10 - 0.93)**

Accounting for unreported crashes and injuries occurring with conventional vehicles causes the crash rate per million miles to increase from 1.9 to 4.1, with a 95% confidence interval from 3.5 to 4.7, and the injury rate per million miles to increase from 0.77 to 1.02, with a 95% confidence interval from 0.88 to 1.16. However, these potentially unreported crashes reduce the overall injury rate per crash[8] from 0.41 to 0.25, with a 95% confidence interval from 0.19 to 0.33.

The results in Table 6 (and Figure 5) indicate that, while the current best estimate is that self-driving vehicles have a *higher* crash rate per million miles traveled than conventional vehicles (9.1 vs. 4.1), the corresponding 95% confidence intervals overlap. Therefore, we currently cannot rule out, with a reasonable level of confidence, the possibility that the actual rate for self-driving vehicles is *lower* than for conventional vehicles.

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[7] When calculating adjusted injury rates for conventional vehicles, it was assumed that the 24% of unreported injury crashes also resulted in 24% underreporting of crash-related injuries.

[8] Because the adjustments for underreporting increased the number of crashes more than the number of injuries for conventional vehicles (as the majority of unreported crashes were property-damage only), the adjusted injuries per crash *decreased*, falling below the rate for self-driving vehicles.

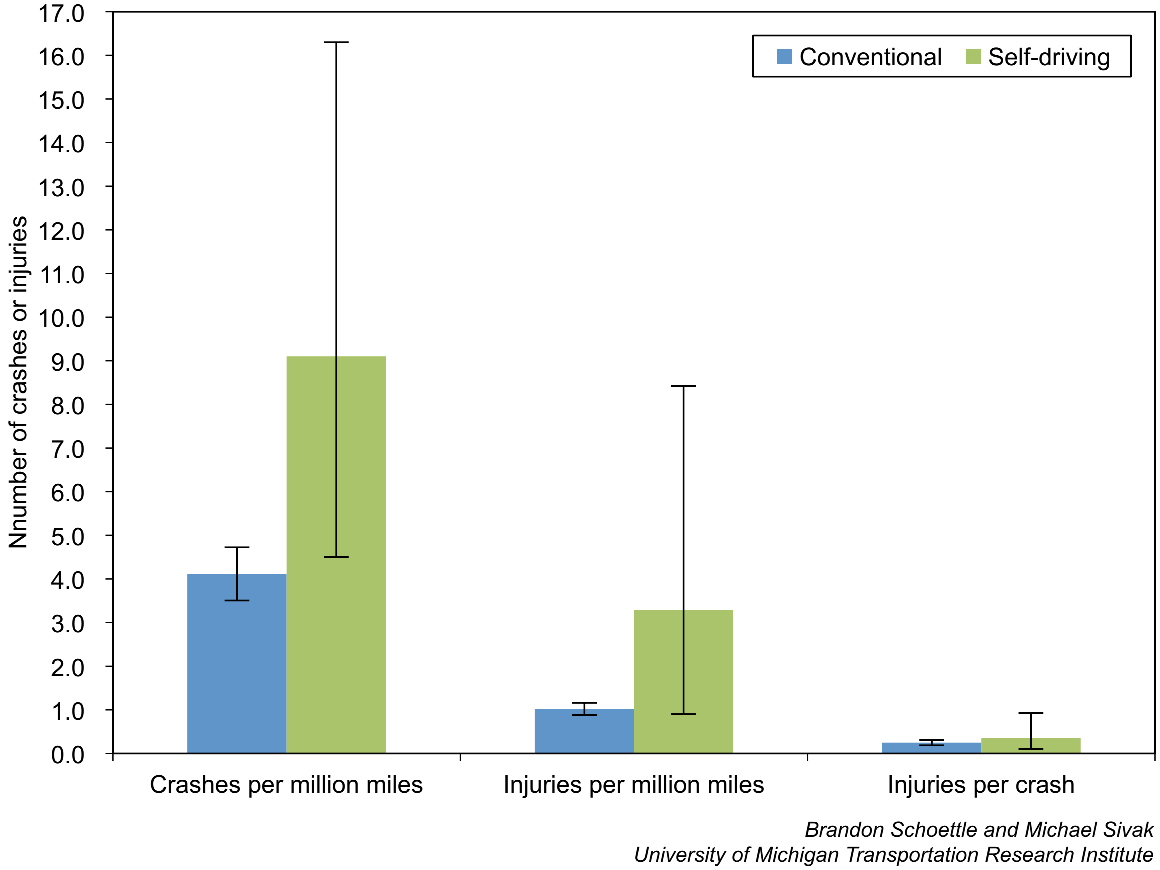

Figure 5. Adjusted crash and injury rates for conventional vehicles and self-driving vehicles, with error bars representing the 95% confidence intervals.

While similar patterns were evident for injuries per million miles traveled and for injuries per crash (the adjusted rates are higher for self-driving vehicles than for conventional vehicles, but the confidence intervals overlap), all injuries from crashes involving self-driving vehicles were minor.

Transitions from autonomous to manual control

As discussed previously in this report, two of the self-driving vehicle crashes included in this analysis involved scenarios where the human driver attempted to retake control of the vehicle from the autonomous system. These crashes were included because the critical events for both crashes developed while the vehicles were in autonomous mode, and there is no indication that the outcomes would have been different if the vehicle had remained in autonomous mode. However, had we excluded those two crashes from the analysis, the overall crash and injury trends would have remained the same, with self-driving vehicles exhibiting higher rates than conventional vehicles. (Removing these two crashes reduces the self-driving vehicle crash rate per million miles from 9.1 to 7.5, compared with 4.1 for conventional vehicles; it reduces the injuries per million miles from 3.29 to 2.47, compared with 1.02 for conventional vehicles; and it reduces the injuries per crash from 0.36 to 0.33, compared with 0.25 for conventional vehicles.)

Other self-driving vehicle fleets

The analysis in this report focused on the on-road experience of three out of ten companies currently approved to test such vehicles on California roads due to the publicly available data for these fleets. However, it is possible that the other seven approved companies have accumulated some unknown (i.e., not publicly disclosed) number of miles on public roads in California, presumably without any crashes or injuries. (This possibility of undisclosed mileage exists for the three companies included in this analysis as well.) Therefore, the actual crash and injury rates for self-driving vehicles are possibly somewhat lower than those calculated in this report, though the additional mileage accumulated by these other companies is likely to be small in relation to the mileage included in this analysis (about 1.2 million miles).

Road safety for conventional vehicles in the U.S. versus California

This analysis compared road safety of self-driving vehicles driven primarily in California with road safety of conventional vehicles in the entire U.S. To the extent that road safety in California is better than the average road safety in the U.S. (Sivak, 2014), the relevant road safety of conventional vehicles is better than that discussed in this report.

At-fault parties in crashes involving self-driving vehicles

The at-fault parties in *all* crashes involving self-driving vehicles were drivers of conventional vehicles. This fact is consistent with the anticipated uncertainty about what to expect from self-driving vehicles on the part of drivers of conventional vehicles (Sivak and Schoettle, 2015).

Conclusions

This study performed a preliminary analysis of the cumulative on-road safety record of self-driving vehicles for three of the ten companies that are currently approved for such vehicle testing in California (Google, Delphi, and Audi). The analysis compared the safety record of these vehicles with the safety record of all conventional vehicles in the U.S. for 2013 (adjusted for underreporting of crashes that do not involve a fatality).

Two important caveats should be considered when interpreting the findings. First, the distance accumulated by self-driving vehicles is still relatively low (about 1.2 million miles, compared with about 3 trillion annual miles in the U.S. by conventional vehicles). Second, self-driving vehicles were thus far driven only in limited (and generally less demanding) conditions (e.g., avoiding snowy areas). Therefore, their exposure has not yet been representative of the exposure for conventional vehicles.

With these caveats in mind, there were four main findings. First, the current best estimate is that self-driving vehicles have a *higher* crash rate per million miles traveled than conventional vehicles, and similar patterns were evident for injuries per million miles traveled and for injuries per crash. Second, the corresponding 95% confidence intervals overlap. Therefore, we currently cannot rule out, with a reasonable level of confidence, the possibility that the actual rates for self-driving vehicles are *lower* than for conventional vehicles. Third, self-driving vehicles were not at fault in any crashes they were involved in. Fourth, the overall severity of crash-related injuries involving self-driving vehicles has been lower than for conventional vehicles.

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