Accident Analysis and Prevention 110 (2018) 136–148

Contents lists available at ScienceDirect

Accident Analysis and Prevention

journal homepage: www.elsevier.com/locate/aap

Full length article

Autonomous vehicles' disengagements: Trends, triggers, and regulatory limitations

Francesca Favarò[a,b,*], Sky Eurich[b], Nazanin Nader[b]

[a] Department of Aviation and Technology, San Jose State University, San Jose, CA, United States
[b] RiSA^{2}S Research Center, San Jose State University, San Jose, CA, United States

ARTICLE INFO

Keywords:
Autonomous vehicles
Transportation safety
Autonomous technology disengagements

ABSTRACT

Autonomous Vehicle (AV) technology is quickly becoming a reality on US roads. Testing on public roads is currently undergoing, with many AV makers located and testing in Silicon Valley, California. The California Department of Motor Vehicles (CA DMV) currently mandates that any vehicle tested on California public roads be retrofitted to account for a back-up human driver, and that data related to disengagements of the AV technology be publicly available. Disengagements data is analyzed in this work, given the safety-critical role of AV disengagements, which require the control of the vehicle to be handed back to the human driver in a safe and timely manner. This study provides a comprehensive overview of the fragmented data obtained from AV manufacturers testing on California public roads from 2014 to 2017. Trends of disengagement reporting, associated frequencies, average mileage driven before failure, and an analysis of triggers and contributory factors are here presented. The analysis of the disengagements data also highlights several shortcomings of the current regulations. The results presented thus constitute an important starting point for improvements on the current drafts of the testing and deployment regulations for autonomous vehicles on public roads.

1. Introduction

Autonomous Vehicle (AV) technology is quickly becoming a reality on US roads. Testing on public roads is undergoing in several states, including among others California, Texas, Nevada, Pennsylvania, and Florida. AV manufacturers are targeting different levels of autonomy, with semi-autonomous vehicles currently in the lead (Favarò et al., 2016).

In semi-autonomous vehicles, a human driver is allowed to cooperate with the software that acts as the "brain" of the vehicle and serves as back-up whenever the software autonomous technology (AT) disengages after a failure. Regulators and manufacturers abide by the classification of levels of autonomy as defined by the Society of Automotive Engineers (SAE), and as reported in Fig. 1, (SAE, 2014).

SAE defined 6 levels of automation, ranging from Level 0 (no automation) to Level 5 (full unrestricted automation). The definition of the six levels (rows of Fig. 1) are based on four factors (the four columns to the right of Fig. 1) as follows:

A The agent responsible for executing steering and throttle control: either human driver or AT;
B The agent responsible for monitoring the external environment: either human driver or AT;
C The agent responsible for serving as "back-up" when a failure prompts a disengagement of the AT: either human driver or AT;
D The driving modes in which autonomous operations are allowed: either "all modes of operations" (meaning unrestricted conditions) or "some mode of operations" (meaning pre-specified conditions, e.g., good visibility).

Levels 1 through 3 are regarded as "semi-autonomous" due to the fallback performance (or back-up) of the driving tasks placed on the human driver. Currently, fully-autonomous vehicles (Level 4 and Level 5) are not permitted deployment on the market (i.e., selling). All Levels of autonomy are permitted to test on public roads as long as they are retrofitted in a way that allows for a back-up human driver (California Department of Motor Vehicles (CA DMV), 2016). Such regulation was imposed by the California Department of Motor Vehicles (CA DMV) to allow AV manufacturers to test the capabilities of the AT that controls Level 4 and 5 vehicles, but at the same time increasing safety of the public by mandating the presence of a control driver who has to undergo a specific training (California Department of Motor Vehicles (CA DMV), 2016). The CA DMV is also in the process of issuing a new regulation for market deployment. The current draft highlights the role

* Corresponding author at: Department of Aviation and Technology, San Jose State University, One Washington Square, San Jose, CA, 95192-0061.
E-mail address: francesca.favaro@sjsu.edu (F. Favarò).

https://doi.org/10.1016/j.aap.2017.11.001
Received 7 August 2017; Received in revised form 12 October 2017; Accepted 1 November 2017
Available online 11 November 2017
0001-4575/

SAE level	Name	Narrative Definition	Execution of Steering and Acceleration/ Deceleration	*Monitoring* of Driving Environment	Fallback Performance of *Dynamic Driving Task*	System Capability *(Driving Modes)*
***Human driver* monitors the driving environment**						
0	No Automation	the full-time performance by the *human driver* of all aspects of the *dynamic driving task*, even when enhanced by warning or intervention systems	Human driver	Human driver	Human driver	n/a
1	Driver Assistance	the *driving mode*-specific execution by a driver assistance system of either steering or acceleration/deceleration using information about the driving environment and with the expectation that the *human driver* perform all remaining aspects of the *dynamic driving task*	Human driver and system	Human driver	Human driver	Some driving modes
2	Partial Automation	the *driving mode*-specific execution by one or more driver assistance systems of both steering and acceleration/ deceleration using information about the driving environment and with the expectation that the *human driver* perform all remaining aspects of the *dynamic driving task*	**System**	Human driver	Human driver	Some driving modes
***Automated driving system* ("system") monitors the driving environment**						
3	Conditional Automation	the *driving mode*-specific performance by an *automated driving system* of all aspects of the dynamic driving task with the expectation that the *human driver* will respond appropriately to a *request to intervene*	System	**System**	Human driver	Some driving modes
4	High Automation	the *driving mode*-specific performance by an automated driving system of all aspects of the *dynamic driving task*, even if a *human driver* does not respond appropriately to a *request to intervene*	System	System	**System**	Some driving modes
5	Full Automation	the full-time performance by an *automated driving system* of all aspects of the *dynamic driving task* under all roadway and environmental conditions that can be managed by a *human driver*	System	System	System	**All driving modes**

Fig. 1. AV levels of automation. Reproduced AS-IS with permission from SAE-International J3016™, (SAE, 2014).

of the human driver, who is responsible *"for monitoring the safe operation of the vehicle at all times, and must be capable of taking over immediate control in the event of an autonomous technology failure or other emergency"* (California Department of Motor Vehicles (CA DMV), 2015). The wording of the deployment regulation (California Department of Motor Vehicles (CA DMV), 2015) again indicates that Level 4 and Level 5 cars are not permitted on the market.

In addition to restricting the autonomy levels permitted on public roads and including the provision for steering wheel and pedals retro-fit during testing, the CA DMV also mandates that reports for AT disengagements during *testing* on state roads be drafted and made available to the public (California Department of Motor Vehicles (CA DMV), 2016). During disengagement of the autonomous technology (AT), the car control authority shifts from autonomous to manual mode, thus handing the control back from the software to the human driver.

Given the safety-critical role of AV disengagements, the authors initiated a study to analyze the entirety of the data filed by AV manufacturers to the CA DMV. Previous work by the authors (Favarò et al., 2016; Favarò et al., 2017) examined in detail all the situations in which AV collisions were reported. On average, 1 event every 178 disengagements leads to an accident (here defined as an actual collision with other vehicles or pedestrian or property). This average is obtained by dividing the total number of reported disengagements (which can be either manually or autonomously triggered) by the total number of reported accidents up to July 2017. The scope of the present work is thus to get an in-depth look at the disengagements reported data, and understand which are the most frequent contributory factors leading to a disengagement. Trends and specific contributions per manufacturer are also analyzed.

Additionally, the work looks at potential limitations and concerns with the current regulations posted by the CA DMV. In fact, the data provided by the AV manufacturers is somewhat fragmented and inconsistent, partially due to imprecise and loose verbiage in the current regulations. The analysis brought forward in this work highlights specific shortcomings that the authors hope will be taken into consideration by the CA DMV for a careful revision of current regulations.

The remainder of this paper is structured in the following way. Section 2 provides an overview of the reporters and of the disengagements database we constructed. Section 3 presents the core of the analysis of the disengagements contributory factors and the taxonomy developed for the study. Section 4 derives results in terms of disengagement frequencies and mileage driven before disengagement. Section 5 concludes this paper.

2. Overview of disengagements reporting

2.1. The notion of disengagement and limitations in its definition

Whether forced by design choices or due to insufficient information regarding the context of a particular situation, an autonomous car can suffer from what it is called a "disengagement mode". During disengagement, the full control and authority of the car movement is handed from the autonomous technology that acts as "brain" of the vehicle to the human driver.

The CA DMV currently mandates that reports for such disengagements during testing and/or field operations be drafted and made available to the public (California Department of Motor Vehicles (CA DMV), 2016). Currently, 36 companies between OEMs, tier-1 suppliers, and tech startups are listed and authorized by the California Department of Motor Vehicle for testing on public roads (full list at https://www.dmv.ca.gov/portal/dmv/detail/vr/autonomous/testing). As of July 2017, only 11 manufacturers have reported disengagements.

The data archive (available at (CA DMV, 2017a)) includes scanned copies organized by manufacturer of all disengagement reports occurred during testing on CA public roads between September 2014 and January 2017. The manufacturers' list includes: Bosch, Delphi

Automotive, Google (now Waymo), Nissan, Mercedes-Benz, Tesla Motors, BMW, GM, Ford, Honda, and Volkswagen Group of America. The data lends itself to statistical analysis, and currently includes a total of 5325 disengagements. For each disengagement, additional data may be provided (e.g., mileage driven by the car, brief description of the event, reported weather, reported road condition, reported presence of other vehicles/pedestrians, etc.), so that multiple entries are associated to each disengagement. Each manufacturer provides its own formatting, resulting in a fragmented set of data. Manufacturers that are testing on CA public roads are mandated to update their disengagement list each year.

Before analyzing the bulk of data reported by the manufacturers, it is important to understand what is intended for "AT disengagement". The CA DMV defines disengagements of autonomous vehicles in the following way:

" […] "disengagement" means a deactivation of the automation mode when a failure of the autonomous technology is detected or when the safe operation of the vehicle requires that the autonomous vehicle test driver disengages the autonomous mode and take immediate manual control of the vehicle." (California Department of Motor Vehicles (CA DMV), 2016)

The definition is particularly meaningful in light of the following consideration. Disengagements can be initiated either manually by the driver or autonomously by the car. This distinction is very relevant from a safety standpoint. Manual disengagements initiated by the driver are cautionary in nature (for instance if he/she feels uncomfortable in a particular situation and/or adopts a proactive approach to prevent a potential autonomous disengagement). Automated ones are indicative of a design limitation of the car and so constitute a potential safety concern on the part of the consumers/general public.

Interestingly, the DMV makes the distinction between manual and automated disengagements only implicitly. While the distinction is subsumed in the definition provided, no mention of it is included in the rest of the regulation, and manufacturers are not required to clearly indicate which disengagements are indeed indicative of an automated system failure (here intended as the incapability of the system to handle a particular situation leading to the control hand-off to the backup human driver). The impossibility to distinguish between the two constitutes a significant limitation of the database the DMV is building, and we urge regulators to rethink this choice and the wording of the regulation (California Department of Motor Vehicles (CA DMV), 2016).

As previously highlighted by the authors (Favarò et al., 2017), the regulation (California Department of Motor Vehicles (CA DMV), 2016) leaves substantial freedom to the manufacturers in terms of the data that has to be reported and the associated formatting. Some of the manufacturers include in the "probable cause" of the disengagement a description that lets analysts understand whether the disengagement was manually or autonomously initiated. For instance, Google Inc. adopts a distinction between two disengagement modes: failure detection and safety operations. The two categories are defined in the following way:

– Failure detection: events where the software has detected a technology "failure" – i.e., an issue with the autonomous technology that may affect the safe operation of the vehicle – the AV will immediately hand over control to the driver (Google categorizes these as "immediate manual control" requests) [6,Google Inc. reports];
– Safety operations: events in which test drivers feel necessary to take control of the vehicle for a variety of reasons relating to the comfort of the ride, the safety of the vehicle, or the erratic or unpredictable behavior of other road users [6,Google Inc. reports].

The two categories can be tied back to the distinction between manual and automated initiation. Use of unambiguous terminology can help interpret the data, and the authors prefer the more intuitive wording of manual vs. automated. **The proposed wording separates the cause of the disengagement** (which may be due to a failure detection and/or be associated with safety operations) **from the actual modality of occurrence** (manual vs. automated). It is our belief that the definition provided by the DMV mixed the two elements. Google reports a total of 465 disengagements, of which 32% initiated manually, and 68% were classified as automated.

The distinction between manual and automated disengagement is also important when we consider the role that the human drivers had in the reported AV collisions up to July 2017. A disengagement does not necessarily lead to a collision, and manufacturers have reported a total of 30 accidents up to July 2017 (Favarò et al., 2017; CA DMV, 2017b). Previous work by the authors (Favarò et al., 2016) indicates that in most reported collisions the tests driver initiated a manual disengagement prior to the collision. This is also a consequence of the training program that all test drivers that act as AV safety-pilots have to undergo before they are allowed on public roads (California Department of Motor Vehicles (CA DMV), 2016). Test drivers are in fact instructed to manually disengage the vehicle at the first indication of a scenario the car is not capable of handling. In some other situations, the disengagement actually occurred after the collision (i.e., the autonomy failed to recognize the hazardousness of the situation before the collision, and at the same time the driver was too slow to manually disengage). All of those situations are rear-end accidents, and the authors highlighted in (Favarò et al., 2016) how the AT suffers from still being unable to detect rear-end accidents, similarly to regular human drivers.[1]

Finally, the DMV requests to specify whether the disengagement was the results of a planned test or not. Only Bosch specifies this, incidentally indicating that all 2068 disengagements they reported were due to planned tests. In this case the wording of the regulation is such that it is open to misinterpretations and/or shortcuts on the part of the manufacturer. For instance, Bosch intended "planned test" as one of the categories of probable causes and contributory factors that the DMV asks to report rather than as an additional request (a problem caused by a possibly misleading comma and "and" junction in (California Department of Motor Vehicles (CA DMV), 2016).[2]

2.2. The creation of a digital database

The "freedom" in the reports formatting prompted the authors to create a digital database for ease of analysis and interpretation of the results. The database features categories that are common among reporting manufacturers and that can encompass the bulk of the available data. Fig. 2 presents a screenshot of the database structure.

The database is organized as follows. Each disengagement is listed numerically following the order in which they are presented by the CA DMV and in chronological order for each manufacturer. The information provided for each disengagement is organized according to nine "information buckets": Vehicle Type, Date, Disengagement Reported Cause, Human Factors Involved, Location, Condition, Type of Disengagement, Weather and Other. Each of these buckets is further divided into subcategories that refine some of the options available (e.g., sunny weather, cloudy, rainy, and so on). The main subdivision involves the disengagement causes and contributory factors, as presented in detail in Section 3. The information buckets and subcategories

[1] Note that manual disengagements are also part of the 5325 entries in the database. Diving the number of disengagements by the total number of accidents gives roughly a 1:178 ratio, as reported in the Introduction.

[2] The DMV regulation (California Department of Motor Vehicles (CA DMV), 2016) states that the disengagement report should include "a description of the facts causing the disengagements, including: weather condition, road surface conditions, constructions, emergencies, accidents or collisions, and whether the disengagement was the result of a planned test of the autonomous technology". Rather than intending the "planned test" requirement as an additional piece of information to be included, Bosch avoided providing all the other information, possibly understanding the last portion of the regulation (i.e., "[…], and whether […]") as a separate category of disengagement.

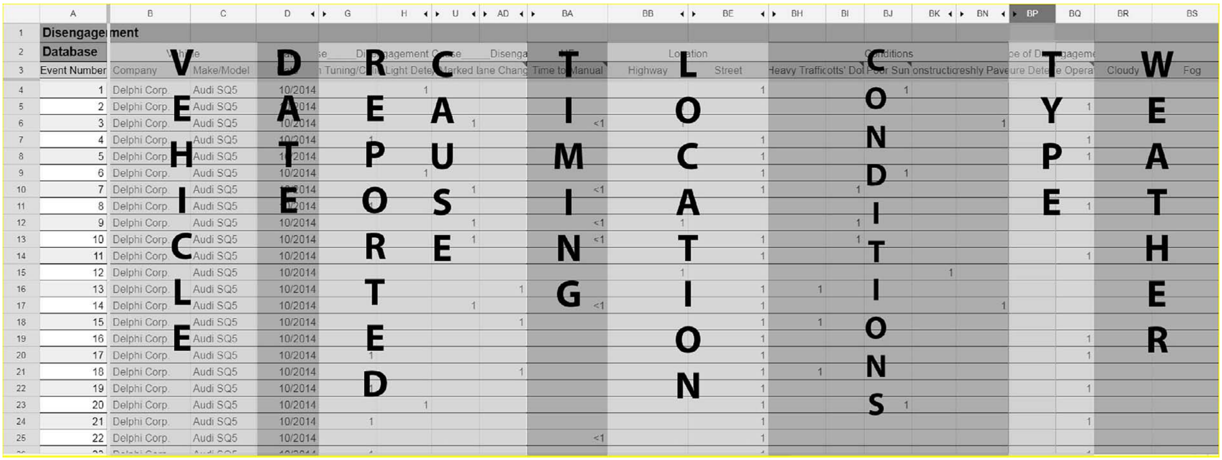


Fig. 2. Sample screenshot of the database structure.

definition is loosely based on a taxonomy borrowed from the Aviation Safety Reporting System (ASRS). ASRS is a NASA run program that collects aviation safety incident reports and acts on the information within those reports to help improve aviation safety. In addition, ASRS maintains a publicly available database that acts as a repository for these reports for research and the promotion of flight safety. One of the authors is an aviation analyst for ASRS and used firsthand knowledge of aviation reporting best-practices when creating the information buckets and sub-categories for the database for the present work. The necessity of creating a consistent database originated from a lack of reporting requirements and consistent methodology in the CA DMV regulation (California Department of Motor Vehicles (CA DMV), 2016). In turn, this caused a fragmented and inconsistent verbiage of reported information, which was distinct to each manufacturer.

2.3. Reporter's overview

Fig. 3 shows the breakdown of the reported disengagements by manufacturer. The data includes reported disengagements from September 2014 until December 2016. The CA DMV mandates that disengagements for each year of activities be reported the subsequent year. The DMV archive was last updated in January 2017 with results up to December 2016.[3]

Previously published research (Dixit et al., 2016) included a brief look at the trends of monthly miles traveled and disengagements encountered by each manufacturer in 2015, also detailing the reasons reported for the disengagements. To avoid repetitions, we do not present the same data here. An additional reason for not doing so is that the trends are mostly inconclusive, with many manufacturers also reporting a reduced mileage for 2016. To provide a better overview of the data, we instead opted to compare the miles driven and the disengagements reported by year, as shown in Fig. 4a,b.

Note that Honda did not report any testing although it owns a testing permit, while Ford and BMW reported testing only for 2016 and Volkswagen only for 2015. Only testing on public roads has to be reported to the CA DMV. Tests on private tracks are permitted and no report has to be filed in those situations. The mileage reported by Google (now Waymo) is not shown in Fig. 4a for clarity (given its different order of magnitude). Table 1 summarizes Google's data.

As gathered from Figs. 3 and 4b, Bosch and Mercedes Benz have the highest number of reported disengagements. Interestingly, Google is driving over 4 times as many miles as Bosch, but only scores a fourth place for contribution to the overall number of disengagements (5325). The different orders of magnitude reported in Table 1 are due to Google fleet size. Google employs a fleet of 60 vehicles (as of 2017) (Favarò et al., 2016), while the other manufacturers average a fleet size of 2 vehicles each (see full details on fleet sizes in (Favarò et al., 2016)). Data for each separate vehicle is provided (in terms of mileage breakdown by month by vehicle) and shows that Google disengagement frequencies are comparable to those of other manufacturers. For this reason, Google is kept within the pool of analyzed manufacturers and not treated separately. A detailed analysis of disengagement frequencies is presented in Section 4.

3. Analysis of AT disengagements: triggers or contributory factors?

Section 2 introduced the database that the authors created for the analysis of the fragmented data obtained from the CA DMV. Fig. 2 indicated the different types of entries associated to each disengagement. At the heart of the author's analysis was the detailed organization of the reported causes, indicated in the third column of Fig. 2. The CA DMV regulation specifies that each manufacturer shall report "a description of the facts causing the disengagement", (California Department of Motor Vehicles (CA DMV), 2016). The verbiage "disengagement cause" is not defined within the regulation, nor is an indication present on a limit for how many "causes" shall be reported, or a structure to identify primary triggers (i.e., events that initiated the disengagement) versus additional contributory factors (i.e., elements that are part of the chain

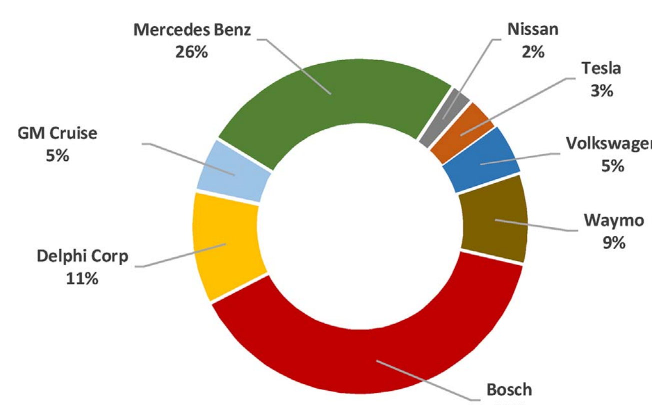


Fig. 3. Breakdown of disengagements reporters. BMW and Ford report 1 and 3 disengagements each, respectively thus rounding to a zero percentage. Honda reports no disengagements. n = 5325, data from September 2014 to December 2016.

[3] The DMV archive is organized by year. In the following we refer to "2015" and "2016" disengagements as reported in the DMV archive. Note however that each archive year does not correspond to a calendar year. Specifically, 2015 reports include part of 2014 (September to December) up and including November 2015; 2016 reports cover the range December 2015 to December 2016 excluded.

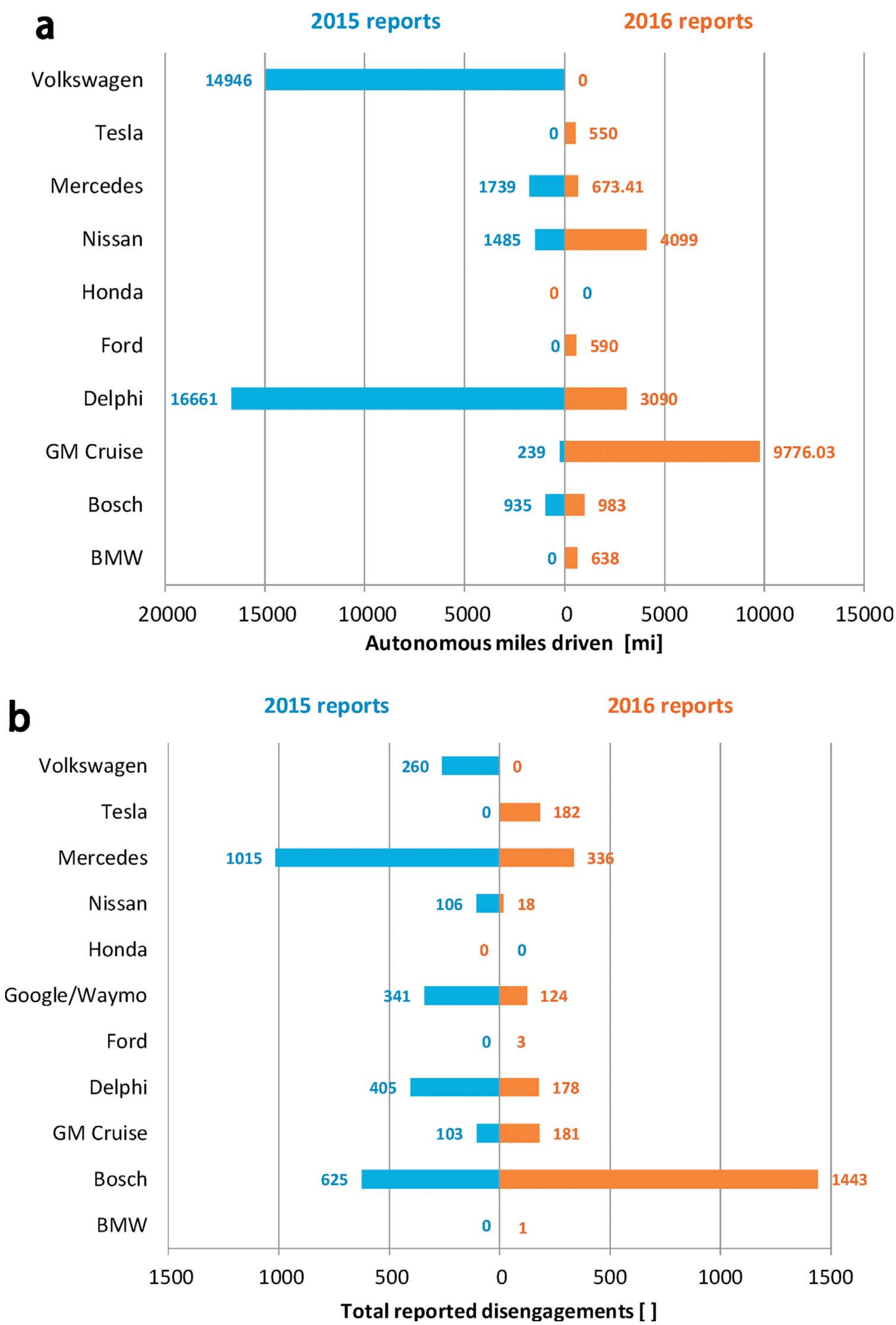


Fig. 4. a) Caomparison of data reported in 2015 and 2016 for autonomous mileage driven across manufacturers. Google data not included, see Table 1. b) Cbomparison of data reported in 2015 and 2016 for total disengagements across manufacturers.

Table 1
Summary of Google data for 2015 and 2016.

Year of testing	Reported Mileage [mi]	Reported Disengagements
2015	424,331	341
2016	635,868	124

of causality, but that if present alone would not have triggered the disengagement). At this stage it is not possible for the authors to create a precise taxonomy, given that each manufacturer reported different causes, in different numbers, and with different formatting. The authors are in the process of drafting a white paper on recommendations to the DMV for a more precise definition of the verbiage used in the regulation.

What the authors opted for was developing a structure to organize the reported causes into macro- and micro- categories to would allow to encompass the bulk of the "causes" reported by each manufacturer. The identified macro-categories are:

1 Human Factors: this category refers to disengagements where the human driver is directly responsible or involved in the decision to initiate the disengagement of the AV technology. Human factors cover a range of reasons ranging from discomfort/general uneasiness to lack of trust in the AV;
2 System Failure: this category refers to a hardware and/or software

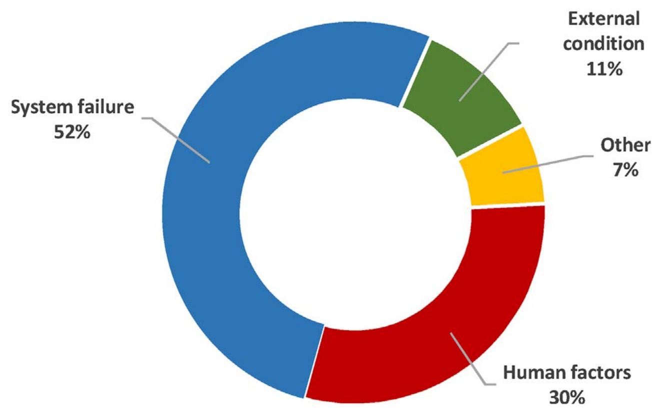


Fig. 5. Breakdown of all reported disengagement into four macro-categories identified for the study. Number of disengagements included in Fig. 5 n = 2616. Only disengagements with clear reported causes could be assigned within the macro-categories. Data from September 2014 to December 2016.

failure of the AV technology that causes the impossibility for the vehicle to continue the autonomous operations. System failure is a broad category that includes issues such as a discrepancy between onboard GPS systems, incorrect perception of external objects, incorrect prediction of other traffic behavior, and so forth;

3 External Conditions: this category refers to disengagements that are triggered by specific conditions related to the external environment. Examples include debris on the road, fading lane markings, or excessive pedestrian traffic;

4 Other: this category was created to account for all disengagements causes in which the specific terminology used by the manufacturer was not directly traceable to any of the previous macro-categories.

The breakdown of the disengagements reported in the four categories is presented in Fig. 5.

Note that the breakdown of Fig. 5 excludes[4]:

- 2068 data points obtained from Bosch, who does not report the probable cause of the disengagements by referring to all its reported data as “planned test” (see Footnote);[2]
- 641 data points from Mercedes-Benz, who reports the probable cause as “technology evaluation”, a category too broad and ultimately inconclusive in assessing the factors with causal relevance to the disengagement.

Each macro-category is further subdivided in micro-categories, organized and inspired by the existing taxonomy adopted in the ASRS database, as explained in Section 2. All the “causes” reported by manufacturers were considered for the creation of 41 micro-categories that would encompass all the inconsistent verbiage used by different manufacturers. Each micro-category was than mapped to one of the four macro-categories identified. Table 2 provides a summary of all micro-categories divided among each macro-category. For each macro-category the micro-categories with higher frequency of occurrence are clearly indicated, while micro-categories with low-priority (i.e., that were only reported a handful of times) are included within an “additional/other” micro-category. A list of all micro-categories included under “additional/other” is provided for each macro-category. Along the numerical data presentation, a visual representation in the form of a pie chart provides the breakdown amongst the higher frequency micro-categories within each macro-category.

[4] There were inconsistencies among the total number of disengagements reported by each manufacturer, and the actual events for which they reported a description. The authors had to manually double-check and count all occurrences from the paperwork submitted to the DMV.

The results of Fig. 5 and the breakdown of Table 2 clearly indicate that system failures have a predominant role in AT disengagements. Within those, reported software-related failures play a bigger role than hardware-related failures, with a ratio of approximately 11:1. One of the reasons that prompted the DMV to mandate the disengagements reporting is to monitor progress that each manufacturer makes every year. Regardless of how and why they are triggered, disengagements initiate the safety-critical process of switching control authority from the AT to the back-up human driver. An AT disengagement is defined and is at all effects a system-level failure, so that prevention and mitigation of the factors that lead to a disengagement is of interest for all manufacturers and the public.

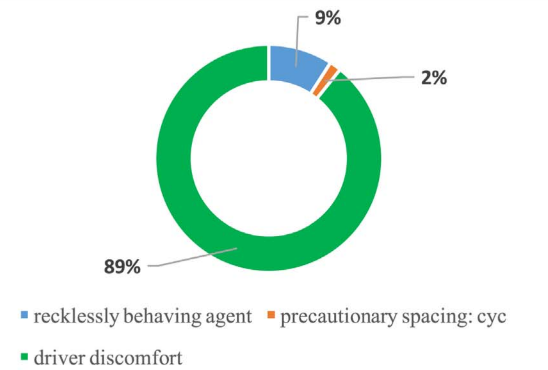
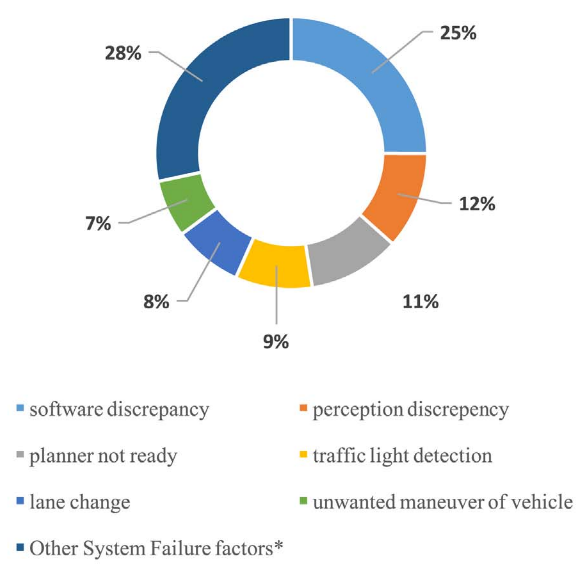
To this end, an interesting point to consider is which categories of those identified in Table 2 can be directly acted upon, and which are beyond the control of the manufacturer and/or the car user. The authors propose a distinction between exogenous and endogenous contributory factors as a new mandatory category that would need to be reported by manufacturers to the DMV. The distinction lies within the possible controllability of the factor, where exogenous/external factors are factors outside the control of the driver and/or manufacturer (e.g., weather conditions, road condition, outside traffic) while endogenous/internal factors can be acted upon. We thus regard the macro-categories of system failures and “other” as endogenous under the direct control of the manufacturer, and the external conditions and human factors category as exogenous (beyond the direct control of the manufacturer/driver).

Exogenous factors are beyond immediate control, but not beyond long-term control. For instance, road maintenance (e.g., re-painting of markings) could alleviate the disengagement occurrence rate, but it is however beyond the direct and immediate control of the manufacturer. It has actually been suggested (Anderson and Biehler, 2014) that AV deployment on public roads may lead to a different approach on how concerns such as road maintenance and liability could be shared between local/federal entities and private manufacturers. For instance, with the interest in mind of improving the success rate of their AVs, manufacturers could target road repaving or other maintenance tasks to prevent and minimize possible external contributory factors to AT disengagements. This idea could empower new ways of how public infrastructure maintenance costs are shared between public and private entities and work towards improving the success of AV deployments on a global scale.

The distinction between exogenous and endogenous factors would also require a careful definition of the categories of causes set forward by the DMV as a mandatory requirement to report (e.g., by providing fillable forms to each manufacturer rather than have each provide its own formatting). This is a necessary step when we consider multiple contributory factors within the chain of causality, and especially the role that weather plays in each reported disengagement occurrence. For instance, we noted how the majority of the sub-categories identified for “System Failure” are software-related. While hardware failures constitute a valid probable cause, the authors recommend that a second layer along the chain of causality should be included for software-related failures. A simple example is instantiated by the category of “incorrect traffic light detection”. This category is indicative of a software system failure; however, the actual probable cause that led to the incorrect detection is not reported. We could for instance assume that a visibility condition might have played a role, rather than the software algorithm design being incapable of detecting a traffic light (in which case, the frequency of occurrence of this micro-category would be much higher). Again, the format of the reported data limits the types of conclusions that can be drawn from it.

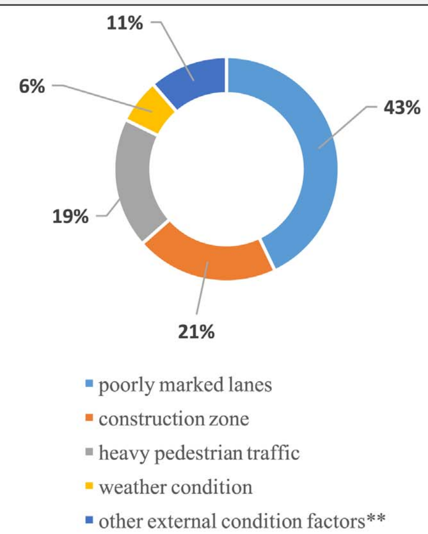
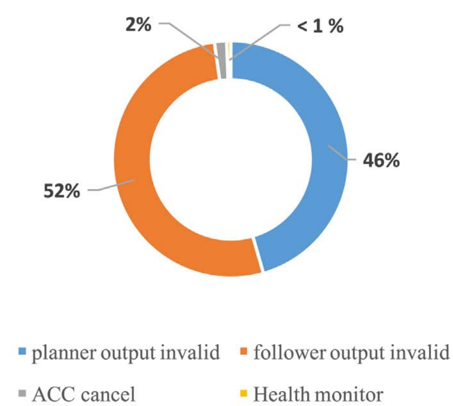
Reported weather conditions deserve a special mention. Adverse weather conditions are here included under the “External Conditions” macro-category. The CA DMV includes weather condition as a mandatory item to report within the list of probable causes of the disengagement. Only Waymo and Mercedes Benz refer to weather as a

Table 2
Breakdown of Macro-categories into Micro-categories for disengagement causes. Continues on next page.

Macro-category	Micro-categories	# of observations	Percentage within category	Percentage in total	
Human Factors	*Recklessly behaving agent*	*72*	*9.14 %*	*2.75 %*	
	Precautionary spacing: cyclist	*13*	*1.65 %*	*0.50 %*	
	Driver discomfort	*704*	*89.21 %*	*26.87 %*	
	Total	***788***	***100 %***	***30.12 %***	
System Failure	*Software discrepancy*	*342*	*25.04 %*	*13.07 %*	
	Perception discrepancy	*158*	*11.57 %*	*6.04 %*	
	Planner not ready	*149*	*10.91 %*	*5.70 %*	
	Traffic light detection	*125*	*9.15 %*	*4.78 %*	
	Lane change	*112*	*8.20 %*	*4.28 %*	
	Unwanted maneuver of vehicle	*93*	*6.81 %*	*3.56 %*	
	*Other System Failure factors**	*387*	*28.33 %*	*14.80 %*	
	Total	***1366***	***100 %***	***52.22 %***	

(continued on next page)

Table 2 (*continued*)

Macro-category	Micro-categories	# of observations	Percentage within category	Percentage in total	
External Condition	*Poorly marked lanes*	*121*	*42.91 %*	*4.63 %*	
	Construction zone	*58*	*20.57 %*	*2.22 %*	
	Heavy pedestrian traffic	*53*	*18.79 %*	*2.03 %*	
	Weather condition	*18*	*6.38 %*	*0.69 %*	
	*Other external condition factors***	*32*	*11.34 %*	*1.22 %*	
	Total	***282***	***100 %***	***10.79 %***	
Other	*Planner output invalid*	*82*	*45.56 %*	*3.13 %*	
	Follower output invalid	*94*	*52.22 %*	*3.59 %*	
	ACC cancel	*3*	*1.67 %*	*0.11 %*	
	Health monitor	*1*	*0.56 %*	*0.04 %*	
	Total	***180***	***100 %***	***6.87 %***	

[a]Please note that the "Other failure factors" category refers to 18 system failure factors with relative percentage lower than 5%. The factors are (largest to smallest percentage): system tuning/calibration, hardware discrepancy, localization error, incorrect behavior predictor, requirement not satisfied, address planning, watchdog error, planner data, vehicle conflict-failure, departure logic, stock vehicle fault, data error, drop off data, AV controller, position estimation, cruise fault, address controls, unknown failure.

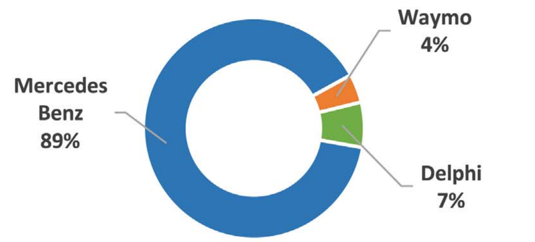
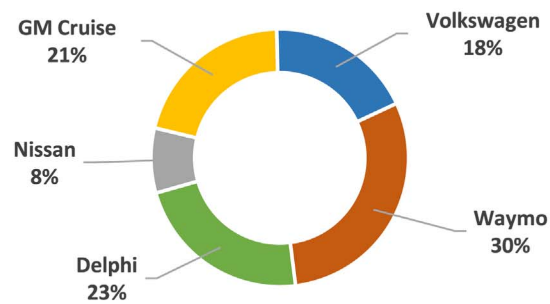
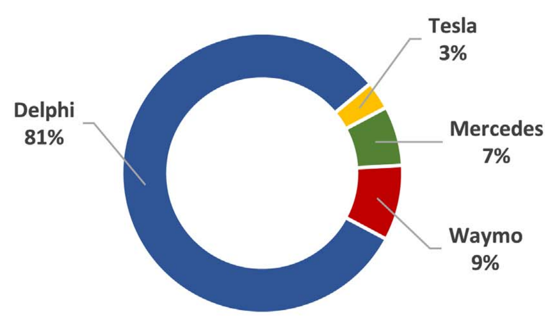
[b]Other external factors category refers to 5 external factors with relative percentage lower than 4%. The factors are (largest to smallest percentage): emergency vehicle, lateral actors, cyclist conflict, vehicle conflict-external, debris on road, poor road condition.

disengagement cause. Other manufacturers, including Nissan, Volkswagen, and Tesla, report the weather condition (and its effect on the road, e.g., wet road) as a separate category, without specifying its contributory effect to the disengagement. In other words, while they report a condition like "snow" or "wet road", such condition is not listed as the disengagement cause reported to the CA DMV. This effect hampers the interpretation of data and the usability of the database, and among other recommendations, we urge the DMV to ensure a stricter abidance to a common formatting on the part of the manufacturers.

To better gather the type of reporting provided by each manufacturer, it is possible to analyze the breakdown of reported macro-categories by manufacturer. Table 3 presents such data in both numerical format and visual format. A possible way to interpret Table 3 is that it indicates to a certain extent the "weak point" or the "focus of interest" of each manufacturer in regards to disengagement reporting. Indeed, the data contained in Table 3 can be read in two possible ways: either indicating the major macro-category that leads to disengagements for each manufacturer, or indicating that a specific manufacturer is mostly focused on analyzing the effects of one particular macro-category. For instance, human factors-related disengagements are mostly reported by Mercedes-Benz alone, indicating that the DMV might opt to recommend to other manufacturers the importance of this contributory factor. Interestingly, the fourth and final macro-category "Other" is only accounted for Tesla, indicating that this manufacturer should provide more detailed explanations of the terminology used in its reporting, or rather abide by the common terminology set forward by the CA DMV.

The macro-categories analyzed in Tables 2 and 3 stem from the disengagement cause reported by each manufacturer (one of the nine

Table 3
Breakdown of manufacturers reporting of macro-categories of disengagement cause. Negligible percentages not shown.

Macro-category	Manufacturers	# of observations	Percentage	
Human Factors	*Mercedes*	*703*	*89.21 %*	
	Waymo	*33*	*4.19 %*	
	Delphi	*52*	*6.60 %*	
	Total	*788*	*100 %*	
System Failure	*Waymo*	*408*	*29.87 %*	
	Delphi	*307*	*22.47 %*	
	Nissan	*111*	*8.13 %*	
	GM Cruise	*284*	*20.80 %*	
	Ford	*3*	*<0.1 %*	
	Tesla	*2*	*<0.1 %*	
	Volkswagen	*251*	*22.78 %*	
	Total	***1366***	***100%***	
External Condition	*Mercedes*	*19*	*6.74 %*	
	Waymo	*24*	*8.51 %*	
	Delphi	*224*	*79.43 %*	
	Nissan	*3*	*< 0.1 %*	
	BMW	*1*	*< 0.1 %*	
	Tesla	*9*	*0.03 %*	
	Ford	*2*	*< 0.1 %*	
	Total	***282***	***100 %***	
Other	*Tesla*	*180*	*100 %*	*Chart N/A*
	Total	***180***	***100 %***	

"info buckets" defined in Section 2.2). In addition to those, other overall conditions are reported, although not necessarily tied as contributory factor to the disengagement occurrence. Those are presented in Figs. 6 and 7 .

Fig. 6 shows a location breakdown of where the disengagement took place. Although required by the DMV, location is not reported in 9% of the cases. Fig. 6 also displays a breakdown by manufacturer.

Fig. 7 presents reported weather conditions for those manufacturers that did not include them as a disengagement cause, as previously explained. The CA DMV does not allow for additional contributory factors other than the main disengagement cause identified by the manufacturer, so that it is not possible to ascertain whether the manufacturer

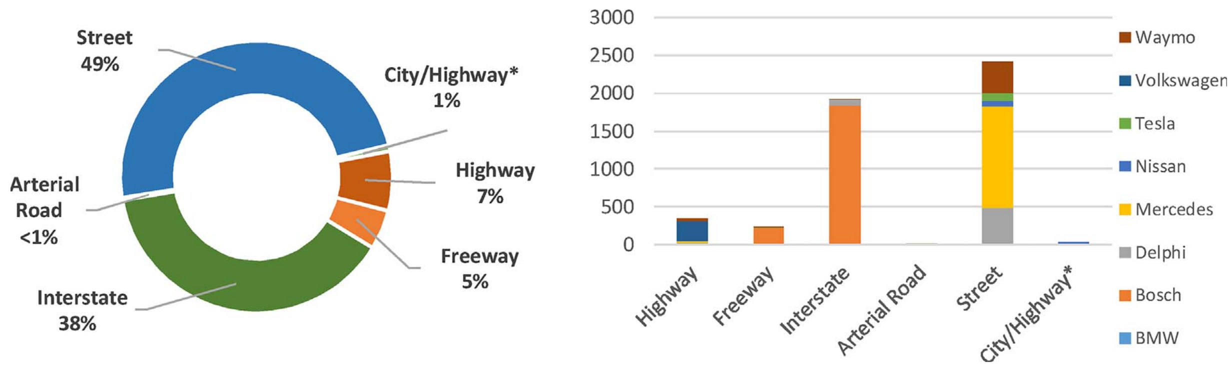


Fig. 6. Reported disengagement location breakdown and distribution by manufacturer. *Nissan reported location as both City and Highway 36 times. Total number of disengagements included n = 4977 (location not reported in 9% of the cases).

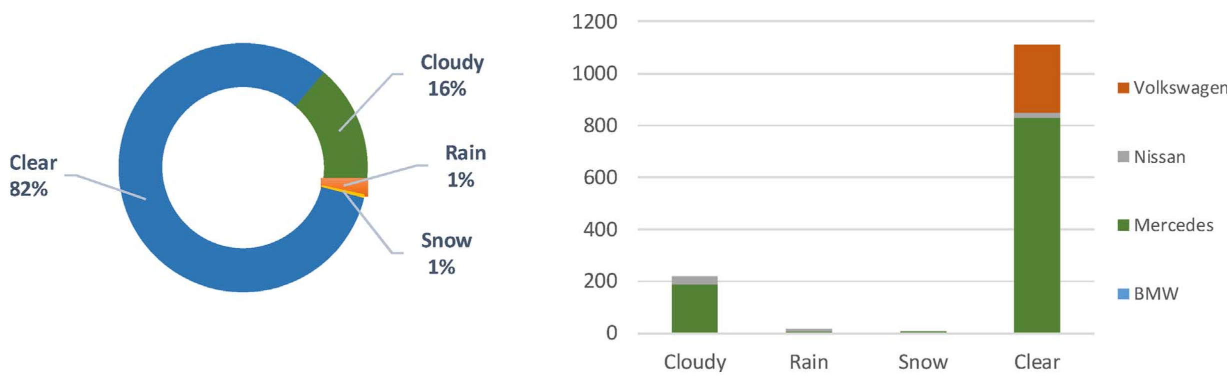


Fig. 7. Reported disengagement weather condition and breakdown by manufacturer. Total number of disengagements included n = 610. Only in 11.5% of the cases weather was reported as an additional entry. Fig. 7 does not include weather reported as "disengagement cause" as found in Table 2.

decided to include and report such information due to its effect on the occurrence of the disengagement. This is another key point we urge the CA DMV to address.

Finally, the database was organized in a way that would encompass all the possible information reported by each manufacturer. It is interesting to analyze, out of the categories that are mentioned as mandatory within the CA DMV regulations, the percentage of missing/incomplete information out of all reported disengagements. This information is conveyed in Fig. 8, which shows in how many instances reported disengagements were not providing all the information requested by the DMV, with a breakdown by the missing category of information.

4. Disengagement frequencies and safety metrics

Similarly, to what was done in (Dixit et al., 2016), Fig. 9 displays the cumulative disengagements as a function of cumulative reported autonomous miles. The slope of the line is 0.0042 (actual regression function $y = 0.0042x + 842$) with a coefficient of determination $R^2 = 0.965$.

Other than showing a similar trend to the preliminary data presented in (Dixit et al., 2016) for 2015 alone, it is interesting to compare the trend of Fig. 9 to a similar plot presented by the authors in (Favarò et al., 2016) that represents the trend of cumulative accidents as a function of cumulative mileage. The plot is also reported here in Fig. 10 for clarity of exposition. The authors in (Favarò et al., 2016) noted that although the number of accidents observed had a significantly high

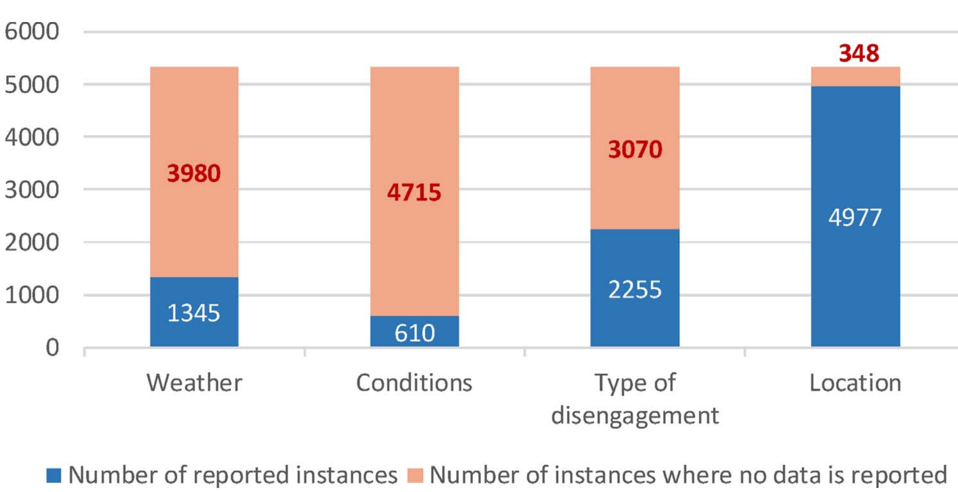


Fig. 8. Breakdown of missing information as reported by manufacturers. "Conditions" refers to additional secondary information provided by manufacturers on external conditions (i.e., presence of botts dots, freshly paved road, faded markings, poor road condition, poor sun, wet road, heavy traffic). Conditions are reported in addition to the primary reported cause of the disengagement.

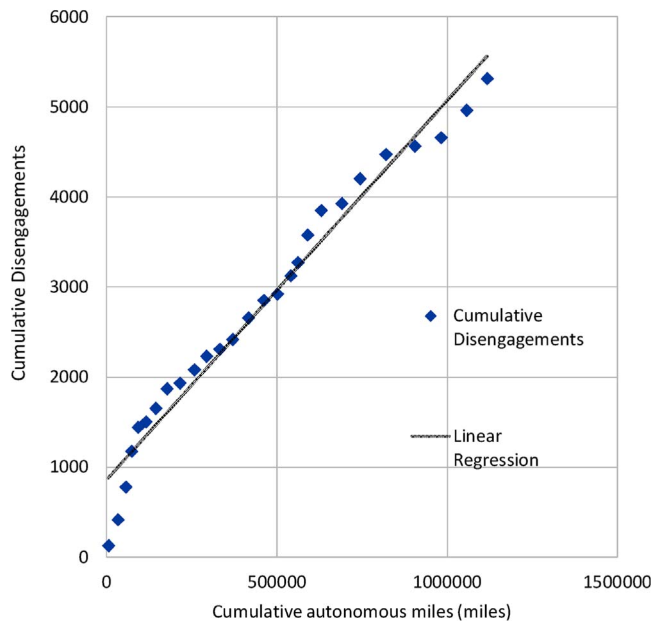


Fig. 9. Cumulative disengagements as a function of cumulative autonomous miles.

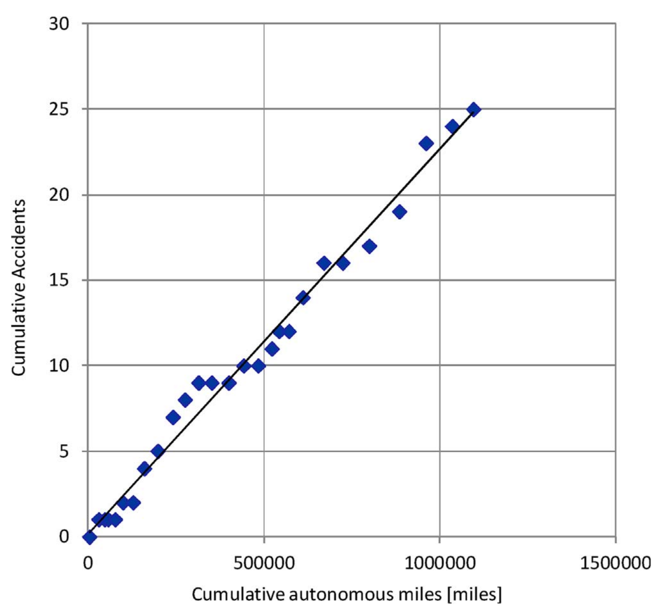


Fig. 10. Cumulative accidents as a function of cumulative autonomous miles, (Favarò et al., 2016). Linear regression function y = 2E − 5x + 0.1562, with coefficient of determination R^2 = 0.986.

correlation with the autonomous miles traveled, these charts could also be examined in function of the technology that powers AVs. Current testing of these vehicles on public roads is used also for the purpose of training the machine learning algorithms that drive the autonomous "brain" of the car. When such algorithms achieve the "fully-tuned" status it will be possible to see that the car is capable of handling more scenarios and avoiding collisions, thus contributing to decreasing the slope of the line shown in Fig. 10, and possibly achieving a steady state plateau region with increasing gaps between subsequent accidents when more miles are driven between each adverse event (and thus an increasing mean time between failures). Similar conclusions can be derived from Fig. 9 as well. Also for Fig. 9, we are still far from reaching the "plateau" region that will be indicative of disengagements-free miles.

Based on the data of Fig. 9, it is also possible to plot the

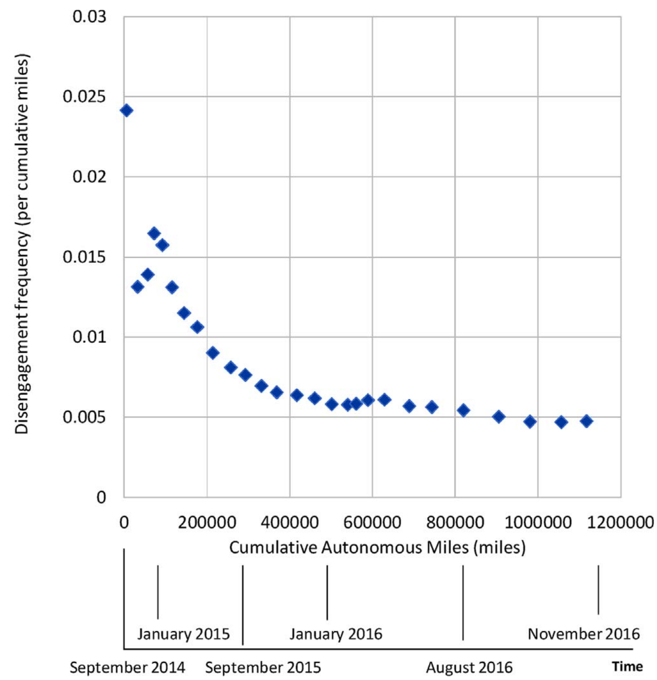


Fig. 11. Disengagements frequency (per cumulative miles) as a function of cumulative autonomous miles and time.

disengagements frequency (per cumulative miles traveled) as a function of cumulative miles or time. The result yields Fig. 11, which highlights that overall (since the plots are obtained across all manufacturers) the AV technology is learning from its mistakes. A key process for the design of safe and efficient AVs is, in fact, the "training" step of the artificial intelligence and machine learning-based algorithms for the AT "brain" of the car. By facing more and more training scenarios, the AV becomes better at handling new situations, after having learned from its mistakes. The trends presented here are preliminary in nature, and many more miles (traveled in real-life or through a simulation environment) are needed before sound conclusions can be derived, (Kalra and Paddock, 2016).

To compute an average "steady-state" frequency across all manufacturers it is possible to divide the total number of disengagements for the total mileage driven by all autonomous vehicles on the road. The obtained disengagement frequency is 4.76e-3 (which is also the final value shown in Fig. 11, units are [1/mi]). This seems a rather large number, especially when compared to the accident frequency for autonomous vehicles that the authors calculated in (Favarò et al., 2016) (total number of accidents divided by autonomous miles driven, units are also [1/mi]). Table 4 provides a comparison of these figures, including the estimated accident frequency for conventional vehicles obtained from (National Highway Traffic Safety Administration (NHTSA), 2016; Federal Highway Administration (FHWA), 2017). The table also shows the inverse of the accident (or disengagement) frequencies, i.e., the miles per accident (or disengagement).

Note that it is only possible to compute accident frequencies and

Table 4
Comparison of estimated accident frequencies for AVs and conventional Vehicles. Data for conventional vehicles obtained from (National Highway Traffic Safety Administration (NHTSA), 2016; Federal Highway Administration (FHWA), 2017).

Type of Vehicle	Accident Frequency [1/mi]	Miles per Accident [mi]	Disengagement Frequency [1/mi]	Miles per Disengagement [mi]
AV	2.38e-5	42,017	4.76e-3	209
Conventional	2.0e-6	500,000	N/A	N/A

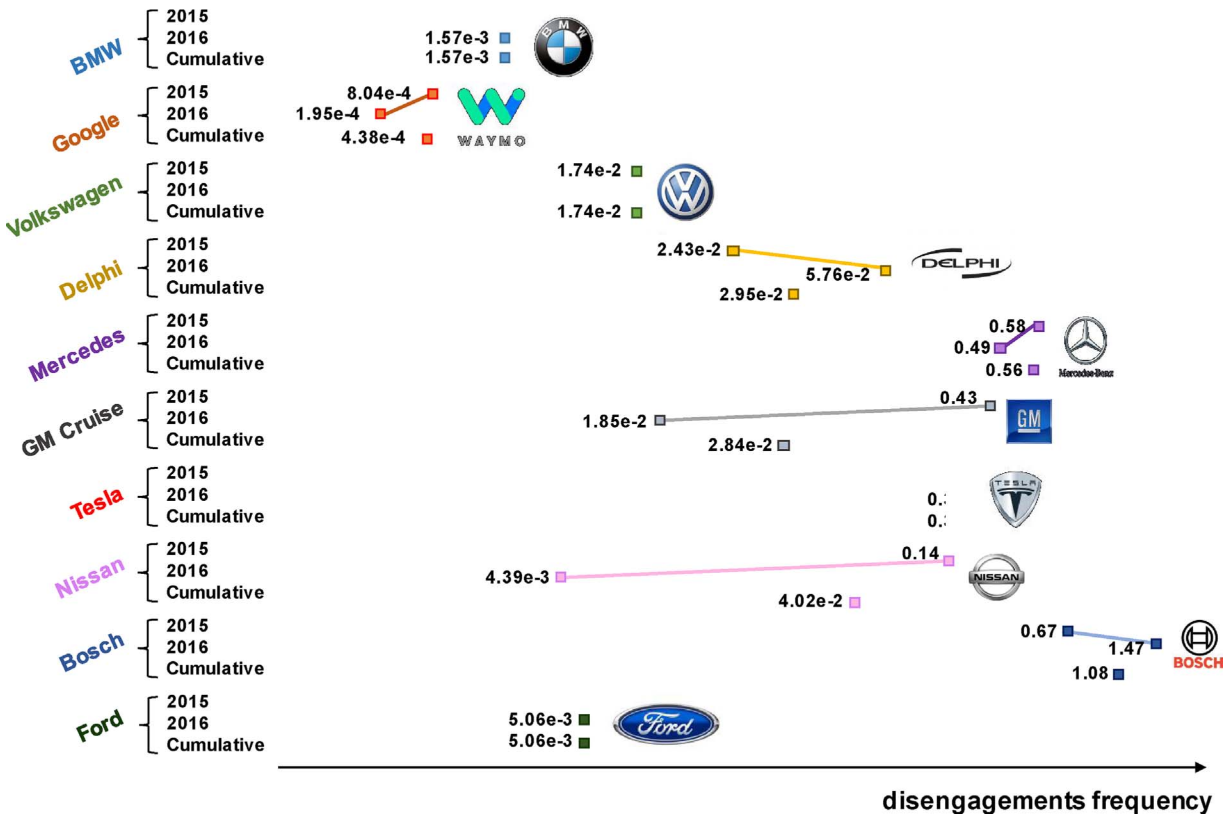


Fig. 12. Trends for disengagement frequencies by manufacturer. Comparison based on data reported in 2015 and 2016 and cumulative frequency. Trends are drawn out of scale for easier interpretation. Trends are drawn only for manufacturers that reported in both 2015 and 2016.

mileage per accident for conventional vehicles, as there is no direct counterpart to disengagements for vehicles that do not present automation. This is an interesting consideration, especially in light of the decision of the CA DMV to make disengagements reporting mandatory for all manufacturers. Given the safety-critical role of AT system-level failures, which translate into a disengagement with the consequent hand-back of the control to the human driver, the authors stand by the decision of the CA DMV to make the disengagements reports mandatory. Currently, the state of California is the only one that is keeping track and archiving any information of AV testing on public roads. The authors believe that such archiving process should be more structured and adopted on a national level, given the potential role of disengagements as AV accidents' precursors and in some cases of a near miss of more dire consequences (Saleh et al., 2013). We believe that the decision of the CA DMV to monitor trends and triggers of disengagements thus adds one layer of defense (with preventive function (Saleh et al., 2014)) against transportation accidents, and is a more pro-active approach than that adopted by other US states.

Finally, the analysis of disengagement frequencies can also be executed by manufacturer. Fig. 12 shows a trend analysis for each manufacturer that compares the overall performance (in terms of disengagement frequency) for 2015 and 2016, and a cumulative result.

Fig. 12 is obtained by dividing all the disengagements reported by each manufacturer by the autonomous miles reported each year. It is interesting to compare Fig. 12 results with those presented in a very similar plot, that of Fig. 13. Fig. 13 also shows the yearly trends of disengagement frequencies per manufacturer. However, this time we only considered disengagements that fall under the endogenous macro-categories of "System Failures" and "Other", indicated in Table 2. The reasoning behind Fig. 13 lies within better framing the relative performance comparison between different manufacturers. Section 3 indicated that exogenous factors are beyond the immediate control of manufacturers, so that it is important to compare performances in terms of endogenous disengagements, especially in the short-term.

Note that the historical trend for each manufacturer does not change when comparing Fig. 12 to Fig. 13. This is indicative of the fact that endogenous disengagements follow the same trend as total disengagements per year (so there is a proportionality in growth or decrease of endogenous and exogenous disengagement, true for each manufacturer). What changes is the relative positioning of some manufacturers compared to others. For instance, Volkswagen had lower frequencies than Delphi in Fig. 12, while Fig. 13 shows them as comparable. Similarly, Nissan has a better performance in Fig. 13. We believe that the usefulness of Figs. 12 and 13 is greater than the reporting of the simple trends of disengagements and mileage driver each month by the manufacturers, which was already presented in (Dixit et al., 2016) and is thus not repeated here. The trends of Figs. 12 and 13 are easily interpreted to understand the performance (and a possible ranking) of each manufacturer. Note, however, that an increased disengagement frequency for 2016 does not imply that the system is becoming "less safe". An increase could simply mean that the manufacturer has broadened the conditions/scenarios in which the car is tested. We would thus recommend to the DMV that the disengagement frequency should also be reported by each manufacturer, together with his historical trend. Should an increase in automated disengagement frequencies be witnessed (or an excessively high frequency as in the case of Bosch), the DMV should also mandate that manufacturers provide a reasonable justification, with potential repercussions on the testing permit should the explanation be deemed insufficient.

5. Conclusions

The paper presented an analysis of the data currently available on disengagements of autonomous vehicles. The data was reported by manufacturers that are currently testing on California public roads to the Department of Motor Vehicles. The results focused on examining

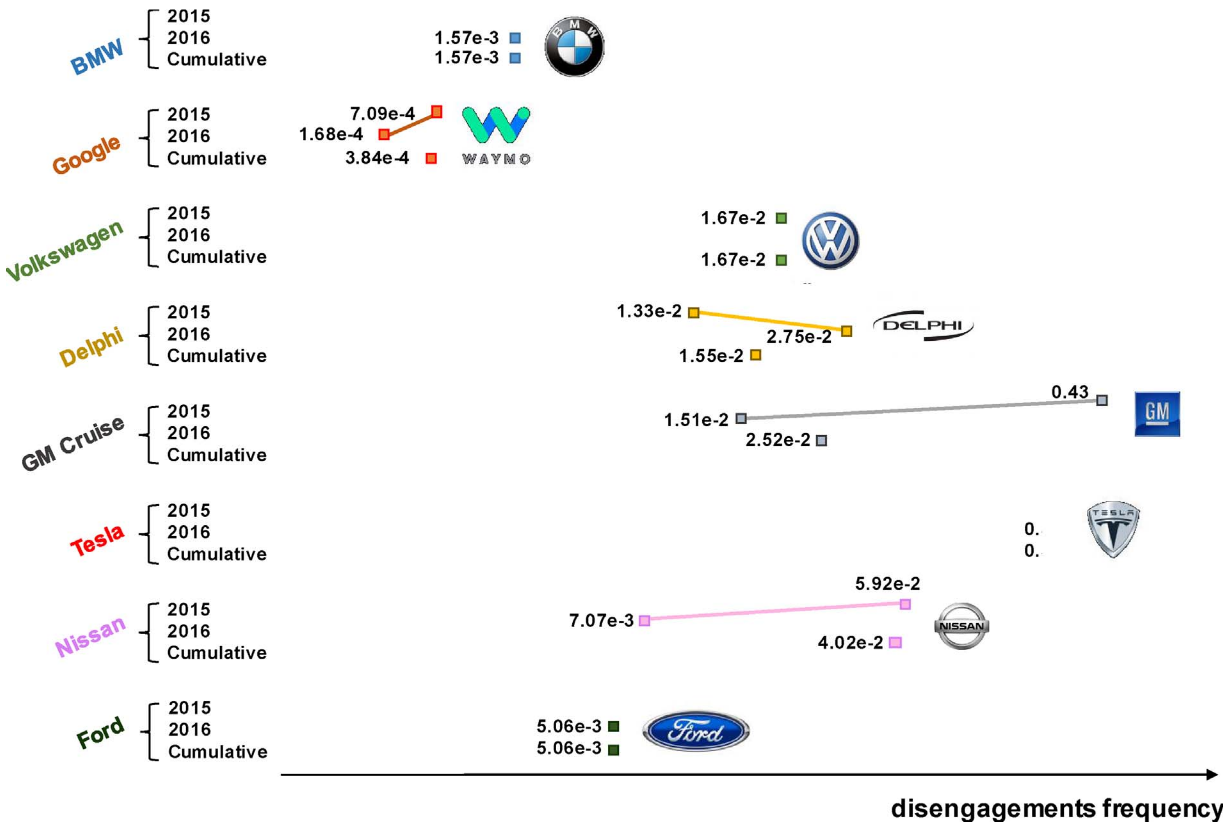


Fig. 13. Trends for endogenous disengagement frequencies by manufacturer. Trends for Bosch and Mercedes are no longer reported as it was not possible to determine whether the reported category of "planned test" and "technology evaluation" would fall under endogenous or exogenous (most likely a combination of the two).

reported contributory factors and probable causes of the disengagements and on drawing preliminary estimations of disengagement frequencies and average mileage driven before disengagement. It was also noted that disengagements do not necessarily lead to an accident (with on average 1 occurrence every 178 disengagements actually resulting in a collision or other injury to people/property). We highlighted the importance of examining disengagements as precursors of transportation accidents, thus providing an added layer of "defense" for safety practitioners and researchers to study contributory factors and prevent future accidents. In these regards, we believe the decision of the DMV to mandate such reports from AV manufacturers was farsighted.

At the same time, we highlighted a number of limitations in the wording and the drafting of the requirements set forward in the regulation for testing of AV on public roads (California Department of Motor Vehicles (CA DMV), 2016) that limit the usability and ease of interpretation of the results. We urge the DMV to recognize these limitations and recommend a careful review of the testing regulation. In particular, we highlighted the importance of the ability to distinguish between manual and automated disengagements, the importance of defining common categories of contributory factors among different manufacturers, and the importance of distinguishing "planned tests" events from probable causes (given that also a "planned test" will test a specific condition that acts as probable cause and/or contributory factor of a disengagement). The authors are currently working on how to inform accident reporting regulations based on the established best-practices available in the aviation industry. The aviation world is a close relative of road transportation with important spill-overs that ought to be considered by both regulators and manufacturers.

Acknowledgements

The authors would like to thank Mr. N. Varadaraju, Mrs. S. Rizvi, and Mrs. M. Tripp for the help on the creation of the disengagement database. This work is sponsored by the SJSU CoE Research Professor Award, and is supported by the Mineta Transportation Institute of San Jose.

References

Anderson, J., Biehler, A., 2014. Self-Driving Cars A Conversation with James Anderson and Allen Biehler. RAND organized talk, Pittsburgh, PA November 5.
California Department of Motor Vehicles (CA DMV), 2015. Summary of Draft Autonomous Vehicles Deployment Regulations December 16. https://www.dmv.ca.gov/portal/dmv/detail/vr/autonomous/auto.
California Department of Motor Vehicles (CA DMV), 2016. Article 3.7–Autonomous Vehicles. Title 13, Division 1, Par. 227. https://www.dmv.ca.gov/portal/dmv/detail/vr/autonomous/testing, September 2016.
California Department of Motor Vehicles (CA DMV), 2017a. CA DMV–Autonomous Vehicles Disengagement Reports. . Archive ? https://www.dmv.ca.gov/portal/dmv/detail/vr/autonomous/disengagement_report.
California Department of Motor Vehicles (CA DMV), 2017b. CA DMV–Reports of Traffic Accidents Involving an Autonomous Vehicle – OL316. . https://www.dmv.ca.gov/portal/dmv/detail/vr/autonomous/autonomousveh_ol316.
Dixit, V.V., Chand, S., Nair, D.J., 2016. Autonomous vehicles: disengagements, accidents and reaction times. PLoS One 11 (12), e0168054.
Favarò, F.M., Nader, N., Eurich, S., Tripp, M., Varadaraju, N., 2016. Examining accident reports involving autonomous vehicles in california. PLoS One 12 (9), e0184952.
Favarò, F.M., Nader, N., Eurich, S., Tripp, M., Varadaraju, N., 2017. Analysis of autonomous vehicle accidents and considerations on human-Machine interactions. Presented at PSAM Topical Conference on Human Reliability, June 2017, Munich.
Federal Highway Administration (FHWA), 2017. Traffic Volume Trends. Available at: https://www.fhwa.dot.gov/policyinformation/travel_monitoring/tvt.cfm.
Kalra, N., Paddock, S.M., 2016. Driving to safety: how many miles of driving would it take to demonstrate autonomous vehicle reliability? Transp. Res. Part A: Policy Pract. 94, 182–193.
National Highway Traffic Safety Administration (NHTSA), 2016. 2015 motor vehicle crashes: overview DOT HS 812 318. Traffic Safety Facts Research Note. pp. 1–9.
SAE. Society of Automotive Engineers. On-Road Automated Vehicle Standards Committee, 2014. Taxonomy and Definitions for Terms Related to On-road Motor Vehicle Automated Driving Systems.
Saleh, J.H., Saltmarsh, E.A., Favarò, F.M., Brevault, L., 2013. Accident precursors, near misses, and warning signs: critical review and formal definitions within the framework of discrete event systems. Reliab. Eng. Syst. Saf. 114, 148–154.
Saleh, J.H., Marais, K.B., Favaró, F.M., 2014. System safety principles: a multidisciplinary engineering perspective. J. Loss Prev. Process Ind. 29, 283–294.