Requirements for the Next-Generation Autonomous Vehicle Ecosystem

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***Abstract*—Autonomous vehicle (AV) technology is a huge leap forward in capability for mobility. To be effective, the current human based vehicle safety infrastructure will have to be upgraded. A critical leg of this infrastructure is the automobile accident report. Conventional vehicle accident reports have evolved to a point where law enforcement have a reasonably standard approach focused on humans. However, with AVs there are no drivers to interview. Also, given their automation, a flaw found in an AV has the potential to be a systemic risk. In this respect, AVs must be handled more like airplanes in terms of post accident procedures. In this paper, we explore the requirements for AV accident reports and the escalation procedures required to avoid systemic risks. Our methodology is to analyze all the information available (crash reports as well as press accounts) of AV accidents to date with a special focus on the fatal accidents. As a result of this work, a recommendation of an AV crash report template, associated escalation procedure, and an infrastructure for accumulated learning is presented.**

***Index Terms*—Autonomous vehicles, Event data recorder, Analysis of AV accidents, Recommendations on AV Eco-System Infrastructure**

I. Introduction

A. Conventional Automobile Regulation

Since 1869, when Irish scientist Mary Ward died in the first recorded automobile accident, vehicle accidents have been a concern for society [1]. Since those days, a sophisticated set of entities operate the current eco-system to manage automobile accidents. Important players in this eco-system include local law enforcement, insurance companies, state licensing authorities, and federal authorities. The current system is based on the model of the perception and decision making aspect of driving being owned by the human driver, and the "action" aspect owned by the vehicle manufacturer.

When a vehicle accident occurs, the first engagement point is local law enforcement which preforms an investigation of the accident. In the process, they generate an accident report which has become somewhat standard. The data scheme for current accident reports include the following information:

- Date, time and location of accident. Sometimes weather conditions are included.
- Drivers and vehicles identifying information.
- Description of accident based on driver, passenger, and other witness reports
- Location of damages and medical issues.

After an accident, a fairly well honed system of insurance companies, lawyers, and the court system arbitrate liability issues between the parties. If the driver is at-fault, the state may revoke driving rights from the driver based on safety concerns. When the fault is with the vehicle, a similar process occurs with the vehicle manufacturer, however in this case, a federal regulator, National Highway Traffic Safety Administration (NHTSA), [2] is involved.

NHSTA is responsible for the licensing of vehicles and uses databases such as Fatality Analysis Reporting System (FARS) to aid in this task. In its activities, NHSTA is seeking to find and fix systemic vehicle issues and provide feedback on safety issues for vehicles. NHSTA investigations are often triggered by consumers through the Office of Defects Investigation (ODI) or Crash Investigation Sampling System (CISS).

Since 2012 about 92% of new light automobiles are voluntarily equipped with an Event Data Recorder (EDR). This technology is analogous to the "FDR" in planes, however the Federal Government has yet to require that all vehicles must have this device installed [3]. In 2010, NHSTA produced an official regulation which defined the EDR and all the parameters which must be recorded by it [4] when it is available. Examples of these parameters include: longitudinal and latitudinal speeds and accelerations, engine throttle and RPM, time, ABS activity, air bags deployment status, role angle of the vehicle, occupants position and many more. Most of these parameters are recorded until a fraction of a second before an event or accident.

In contrast to the automobile industry, the FAA requires a "black box" consisting of a flight data recorder (FDR) and cockpit voice recorder (CVR). With the Aviation Safety Reporting System (ASRS), safety concerns can be confidentially reported for further analysis. Finally, after the accident, a well structured interview process is used to provide more insight.

B. AV Accident Reports

The conventional system is optimized for a model of humans as drivers. However, with an AV, the vehicle performs the perception and decision making aspects of the driving operation. This massive shift in responsibility has created several open questions about the nature of who owns the liability, how AV licensing occurs, and how NHSTA can license/manage an AV fleet.

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Various states have taken different approaches for regulation of AV as a driver. California DMV started the process of adopting regulations for testing autonomous vehicles in 2014. In a followup amendment in 2018 [5], these regulations required the manufacturers to submit a report within 10 days of the accident which include level and location of the damage to the vehicle, general heading, road surface condition (wet, dry, holes, etc), visibility (foggy or clear) and whether the AV hit another vehicle or a stationary object.

In addition, the California AV testing regulations made it obligatory for every manufacturer, if authorized to test their AVs on California's public roads, to submit a yearly report that lists all the disengagements of the AV technology during testing. This "disengagement report" is due by the first day of each year. Prior to 2019, there was no structure to the disengagement report, but starting this year, all manufacturers will have to submit a specific form which should help organize the information which will be provided. Beyond California, none of the other states provide guidance on AV accident reports.

C. Related Work

Previous research in this area has focused on collecting AV crash data from current sources [6] [7], and then performing some preliminary data analysis. These studies agree that the current crash reports (when found) are unstructured and that impedes the learning and analysis work. There has been little work in analysing the completeness of the information or suggestions for mechanisms to capture and analyse systemic issues.

This paper addresses these issues by first describing the core architecture of AV systems in Section II. Section III describes our analysis of current crashes from the point-of-view of developing a safety methodology. Section IV presents our recommendations for an updated AV eco-system infrastructure. Finally, Section V offers conclusions.

II. Architecture of AV systems

In order to understand the root causes of AV accidents, it is important to understand the underlying structure of AV systems. The operation of an AV relies upon three major phases of operation: perception, decision making, and taking action. Figure 1 shows the major components of an AV according to these steps. In a conventional vehicle, the perception and decision making steps are controlled by the human driver and the action is executed by the car. The action component is well structured since the automotive industry has more than 100 years of experience in the execution of 'action' stage. However, the perception component (sensing the surroundings) is relatively new and it includes using sensors such as radar, lidar, and cameras in combination with object recognition AI engines. Added to this perception capability are communications from other vehicles (V2V) and infrastructure (V2I). The combination of these capabilities create an internal model of the external environment for the AV.

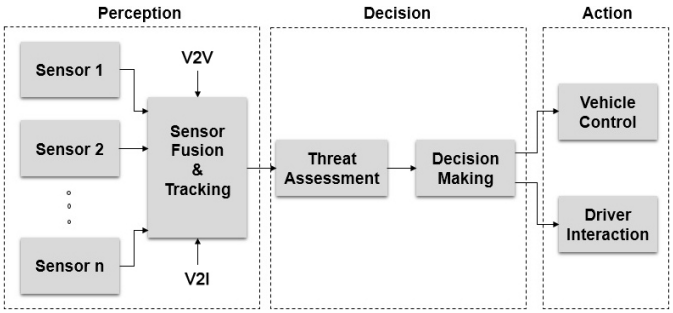

Fig. 1: Autonomous vehicle technology architecture

In the context of accident reports, it is critical that sufficient information is captured to analyze the perception and decision making aspects of the AV. Looking at the architecture of AVs, when an accident occurs, several open questions come to mind. These include:

- Are the sensors working correctly ? as designed ?
- Is the sensor fusion/object recognition correct ?
- Is the obstruction analysis/threat assessment correct ?
- With perfect data, is the AV making the right decision ?
- Is internal data (maps) accurate ?
- Is the V2I or V2V communication correct ?

We will now examine whether we can diagnose these issues with current information.

III. Analysis of Current Accidents

In order to understand the future needs of accident reports, a deep analysis of all the accidents to date was performed. Special focus was placed on major accidents where more information was available in press accounts.

A. Data collection

Our data collection methodology consisted of mining several sources (California DMV and Press) and placing the information into an internal database. The initial schema of the database included:

- The location of the accident expressed in Geographic coordinate system
- Traffic description
- Types of the roads
- Date and time of incident
- Atmospheric conditions
- Manner of accident
- The speed of the vehicles involved, and the speed limit on the road
- The AV company operating the vehicle
- Models of vehicles used
- Severity of accident (fatal / non fatal) and
- The autonomous mode used during the incident

Similar to the experience of past researchers, a critical challenge was to convert unstructured loose textual data into formats which would yield deeper analysis. For minor accidents, it was not unusual for the data to be incomplete,

so the database was populated with whatever information was available. The database was augmented with situational analysis by using the location of the accident and Google Earth to find some static information not in the accident report.

B. Detailed review of minor accidents

The collected data of the AV crashes in the database was analyzed and summaries of the analysis findings are listed in tables I, II and III . In summary, the vast majority of accidents are in sunny areas (bay area, Phoenix, and south east), intersections dominate AV accidents, and most AV accidents are at low speed. These findings agreed with previous analysis [2] of this work which gives us confidence in the integrity of the data.

TABLE I: The list of types of roads or intersections where accidents occur.

Road Type	Accidents (percentage)
Road	8.33
Highway	9.38
T-intersection	13.54
4-way Intersection	63.54
5-way Intersection	4.17
Intersection	1.04

TABLE II: The speed range and the corresponding percentage of accidents for the AV and other vehicle/ object V2 for each speed range

Speed Range (mph)	AV (Percentage)	V2 (Percentage)
0-5	60.71	1.79
5-10	5.36	0.00
10-15	3.57	0.00
15-20	12.50	46.43
20-25	5.36	0.00
25-30	0.00	21.43
30-35	0.00	3.57
35-40	0.00	12.50
40-45	3.57	0.00
45-50	1.79	5.36
50-55	0.00	1.79
55-60	0.00	0.00
60-65	1.79	3.57
65-70	1.79	3.57
70-75	1.79	0.00
75-80	1.79	0.00

Overall, these are not surprising findings given the fact that AV testing has been limited to nice weather and low speed situations. Also, it is well known that intersections cause complexity for AVs. However, a somewhat surprising finding was that the vast majority of AV accidents are actually humans hitting AVs. This begs the question of why? A thesis being developed in the AMI (Advanced Mobility Institute) team is that humans rely on a "language of driving" to communicate their intentions with each other. Finally, minor accidents from AVs receive the same attention as minor accidents with humans. Given the systemic risks, this may not be appropriate.

C. Detailed review of major accidents

Major accidents provide more opportunity for analysis of the required information based on wider media reports. With this section, we analyse each accident and then discern the information which would have been useful for further analysis.

TABLE III: Types of accidents and their percentages while the AV system was engaged or disengaged.

Type of Accident	AV Mode	
	Engaged	Disengaged
A vehicle rear ended AV	60.9%	33.3%
AV rear ended a vehicle	4.3%	7.4%
AV backed into a vehicle	0.0%	7.4%
Side Collision (Perpendicular)	2.9%	11.1%
Side Collision (Angle)	15.9%	22.2%
Side Swiped	7.2%	3.7%
Pedestrian	1.4%	0.0%
Hit a barrier or Stationary object	1.4%	7.4%
front to front	0.0%	3.7%
Other or N/A	4.3%	3.7%
Crossing red light	1.4%	0.0%

1) Uber in Tempe: **Details of Accident:** Based on accident report and news accounts, the first reported AV fatal accident was a pedestrian in Tempe Arizona and occurred on March 18^{th}, 2018 at around 10 pm [8]. A 2017 Uber Volvo SUV working in autonomous mode killed a woman on Mill Ave while she was crossing the road outside the designated crosswalk with a bicycle. The AV was traveling at roughly 40 mi/h. Based on police reports, the backup driver of the AV had no sign of impairment at the time of accident [8].

The National Transportation Safety Board (NTSB) preliminary report showed that Uber disabled Volvo's factory-equipped ADAS features, including the Automatic Emergency Brake (AEB). Uber stated that their self-driving system depends on the human operator of the vehicle to intervene in case of a system failure during the testing. Uber explained that the emergency braking maneuvers were not enabled in order to minimize the potential of any errors in the vehicle behavior when it is in the autopilot mode [9].

The NTSB report states that the AV's speed was 43 mph when the accident happened, and was able to register the observation of the pedestrian (victim) approximately 6 seconds before the accident. As the path of the vehicle and the path of the pedestrian converged , the vehicle's software initially classified the pedestrian as an "unknown" object and then as a vehicle and after that as a bicycle with different expectations of subsequent travel path. It was determined by the vehicle's self-driving system that emergency braking was required in order to reduce the impact of the collision but only 1.3 before impact [9].

Analysis: Given the information, it appears that the AV sensed the object but did not recognize it as a threat. Threat or obstruction analysis is one of the critical issues in the development of AVs. This accident seems to amplify the need for capturing and storage of the object stack between the perception and decision making stages of the AV stack. This would quickly eliminate concerns about sensor failure or environmental conditions. Further, it argues for a time-based classification of the object model between obstruction, threat, and benign. At this point, the critical remaining question consists of understanding what aspects of the object confused the AV ? Without more detailed information, it is impossible to discern whether this problem is actually a systemic risk.

2) Tesla in California: **Details of Accident:** A second fatal AV accident took place in California on March 23^{rd}, 2018 at 9:27 a.m. This accident involved the semi-autonomous vehicle Tesla Model X which slammed into a roadside barrier and then caught fire on highway 101 southbound near Mountain View. The autopilot of the car was engaged prior to the crash and the adaptive cruise control follow-distance was set to minimum.

The preliminary crash report from the NTSB's and the performance data downloaded from the vehicle revealed that during the continuous autopilot operation, the vehicle provided two visual alerts and one auditory alert for the driver to take the steering wheel. These alerts came more than 15 minutes before the crash [10]. The data shows that during the very few seconds before the crash impact, the drivers hands were not detected on the steering wheel and Tesla was steering left following a lead car up to three seconds before the impact. At that time, Tesla increased it's speed from 62 to 70.8 mph and there was no record of braking or evasive steering [10].

Analysis:

This accident highlights the need to understand several factors in the situation. The use-model of autopilot is to follow a leading car while navigating other traffic and road curvature conditions. Several questions come to mind:

- use-model: Is the use-model stable? what happens if the lead car exits? what happens if a new car jumps in between?
- perception: This model requires near continuous perception of the lead car. What happens if interrupted?
- control system: The feedback system with the leading car forms a control system. Is it stable under all conditions?
- human machine: What were the warnings? what should be the behaviour when warnings are ignored?

In terms of accident analysis, it would be useful to know the object model "seen" by the AV as well as the "object" that it was following.

3) Florida Tesla: **Details of Accident:**

The third fatal accident took place in Florida on May 7^{th}, 2015. A semi-autonomous Tesla Model S70D was nearing an intersection on highway 27 and collided with a tractor-trailer that was making a left turn across the path of the Tesla. The Tesla driver, who was killed in the accident, was using the semi-autonomous autopilot mode on his car. The driver received several visual and audio warnings to take control of the vehicle before the crash, according to a report from the NTSB. Despite the warnings, the driver kept his hands off the wheel before colliding with the truck. Visibility for both vehicles was clear and unobstructed and the Tesla driver had around 7 seconds to initiate an avoidance action. However, multiple sources of possible distractions were present inside the Tesla that kept the driver away from taking control of the vehicle [11].

The Tesla Model S70D failed to stop and it drove under the trailer. Tesla claimed Tesla's camera, which is black and white only, was not able to distinguish between the trailer's side color, which was white, and the shiny blue sky's color. Moreover, there is a possibility that the camera was deceived into believing the road was clear ahead because of the height of the trailer. If the system had used different sensor such as LIDAR instead of the camera, it is likely that the colors would not have mattered and probably such accident could have been prevented [12].

Analysis:

This situation highlights complex scenarios which can fool a perception engine. Again, it would be useful if the object model as seen by the Tesla was available. Some have suggested that V2V and V2I communication can be used to solve some of these complex issues.

A recent Mobileye incident helps to highlight the issues in this domain. On May 17^{th}, 2018 Mobileye, the Intel-owned manufacturer of driver-assistance systems, held a media event, to publicly explain a car safety concept called the Responsibility-Sensitive Safety (RSS) model. Mobileye offered a group of reporters the opportunity to ride inside Mobileyes autonomous vehicle (Ford Fusion) and navigate the streets of Jerusalem. Mobileye AV was equipped with 12 cameras and did not use any other sensors [13].

The TV reporters riding the AV had television cameras and while the AV was navigating, it went straight through a red light about a quarter of mile from the companys garage. The Mobileye safety driver of the AV, who was monitoring the car, allowed the car to proceed without trying to stop it [14].

Mobileye said that the incident was not caused by a software problem in the car. Instead, they blamed the electromagnetic interference (EMI) between a wireless camera used by the TV crew and the traffic lights wireless transponder. Mobileye had equipped the traffic light with a wireless transponder for extra safety on the route that the AV was scheduled to drive in the demo. As a result, crossed signals from the two wireless sources befuddled the car. The AV actually slowed down at the sight of a red light, but then zipped on through the intersection [13]. No one was hurt in this incident despite the fact that the video from the AV shows three pedestrians standing at the right hand side of the traffic light but they weren't crossing the street at the time of the incident.

This incident demonstrates the potential for electromagnetic interfere and thus the need to track all communication in the proximity of the accident. This needs to be done in the AV as well as the infrastructure with an ability to lookup based on the time of accident.

IV. Recommendations on AV Eco-System Infrastructure

Based on our analysis of the accidents to date, the current information collection mechanisms, and the operational fundamentals of AVs, AV eco-system upgrades are needed in three places. These are:

- Upgraded Event Data Recorder (EDR) for vehicles and infrastructure
- Upgraded Vehicle Accident Report
- Upgraded FARS and an automotive ASRS system

A. EDR Information

Because the driver cannot be interviewed and AVs are sufficiently complex, Event Data Recorders should be a requirement for all AVs. AV-EDRs should collect the current vehicle dynamics information and in addition capture AV related data. The major categories of AV critical data include raw sensor feeds, all V2V and V2I communications, the ongoing environmental object model resulting from the perception stage, and finally the threat annotations of the object model. In addition, AV-EDR data should be recorded locally and on the cloud in standard formats.

Raw time-based recordings of the sensory systems (camera, lidar, radar, etc) combined with the vehicle dynamics provide the primary physics based modeling information for the AV. With this information, one can determine issues related to manufacturing faults, electromagnetic interference, or weather related faults.

Recording all V2V and V2I information is critical to diagnosing interference issues in the case where communication was intended but was unsuccessful. In addition to the communication, the actual message contained within the communication can be faulty. As an example, the MAP primitive information for an intersection in DSRC can be inaccurate or even malicious based on cyber hacking.

Recording the perception object model and the associated threat annotations is critical in understanding issues of object recognition. The AI systems which are at the center of these systems are perhaps the most challenging to build and verify. If there is a fundamental fault in these systems, it is likely that fault will manifest itself in other situations. Thus, these sorts of errors can pose a systemic risk well beyond the local accident.

In addition to the recording of vehicle systems, the surrounding infrastructure should also record all V2I communications on the cloud which we can call I-EDR. The combination of AV-EDR and I-EDR form a reasonably complete packet of automatically collected information for the accident. Upon accident, law enforcement at the scene should have instant access to the AV-EDR and I-EDR information.

B. AV Police Accident Report

Police officers are well trained to handle human related traffic accidents. However, the current accident procedure needs to be upgraded on three fronts: severity, driver interview, and human interviews. On the severity front, today, minor accidents are treated lightly. This is rational procedure because the behaviour of human beings is well understood. However, the behaviour of AVs is not well understood. Further, minor accidents can indicate safety issues which may lead to major accidents and be systematic. Thus, for AVs, law enforcement should take extra effort for AV minor accidents.

Since law enforcement cannot interview the driver, they need to learn to the "see" the world through the "eyes" of the AV and capture critical information. For the perception step, we recommend they take pictures from the point of view of the AV, look for any notable activity which might impact radar, Lidar, or anything of note in the auditory spectrum. Examples include weather conditions, power lines, or radio equipment. Finally, for the decision making/threat step, they should note any activity which may fool an AV. Examples include pedestrian activity on the sidewalks, small animal activity (squirrels, pigeons, alligators) on the road, or non-standard transportation objects (trucks, scooters, etc).

Finally, for human interviews, since accidents can be caused by human's perceptions of AVs, it is important to understand how the AV was "communicating" with humans in their surroundings. If an AV has erratic behaviour as perceived by humans, it is as much a danger on the road as any erratic human. This interview is especially important for situations where humans hit AVs even in minor fender-benders.

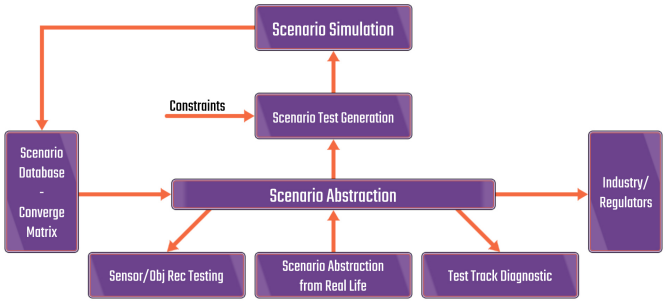

Fig. 2: FPOLY Verification Environment

C. Accumulative Learning Flow

With the combination of the AV-EDR, I-EDR, and AV Police report (collectively the AV-Accident Packet), an assessment can be made around escalation procedures for systemic risk. In this context, software and algorithmic issues are the most severe because they are exactly replicated across all AVs. These issues should be noted and escalated quickly. Hardware sensor failures are important and may indicate longer term reliability issues, but are unlikely to cause systemic issues. Finally, humans hitting AV's should be taken seriously, but is unlikely to demand immediate escalation.

In the context of an overall safety paradigm, individual accidents are very important data points. In order to effectively use accident data, one must build an ability to fold accident information back into the product development and verification flow, and one must build a database which can be mined to find systemic issues not easily exposed at a local scope.

Florida Polytechnic University (FPU)'s Advanced Mobility Institute (AMI) has built a leading edge verification framework as shown in figure 2. Similar to many such frameworks, the vast majority of the validation is done in simulation due to the advantages of cost, safety, controllability and observability. A very important piece for all such frameworks is to provide a feedback process from field data such as accidents.

With the AV-Accident Packet, the accident can be re-created in simulation, and this is invaluable for several purposes. First, the recreation can help with the diagnosis process. Second, once corrective action has been taken, the validation platform

Fig. 3: The locations of AV accidents.

can test the correctness of the action. Finally, derivative test cases can be easily generated to find similar (or "cousin") situations, and correct them at the same time. Thus, the flow from the AV-Accident Packet to the AV verification environment forms a critical feedback process for the overall safety of AVs. To enable this flow, a web-based application was designed to illustrate the information of accidents. Figure 3 shows an access method to this database through a mapping function available at www.flpolyami.com. With this capability, it is possible to locate an AV accident and find the exact location dynamics of the accident on google maps.

Currently, FARS records conventional accident data, and is used to find systemic issues. With AVs, this database will have to extended for AVs with database schema which track issues such as sensor reliability, edge-case conditions which cause perception or threat mapping issues, and even extraordinary weather conditions which are especially problematic for AV safety. As an example, solar flair activity is well known to impact GPS accuracy, so it might well make sense to have some notion of an AV-index in weather reports. Similar to a heat-index or boat-safety, this index would track the impact of weather on AV systems.

Finally, AV systems are very much in their early stages and much needs to be learned on how to build, deploy, and regulate them. In this context, there is an intense need for information from all entities. Thus, an AV equivalent of ASRS is vital. In this case, confidential input can be provided from all sources to help insure the public does not have to face unsafe conditions.

V. Conclusion

Autonomous Vehicles offer the promise to fundamentally make life better for society. However, in order to do so, the current human based infrastructure around automobiles must be upgraded. A key component of this infrastructure is the process to deal with accidents. This is especially important for AVs because they are a new technology and an error in the AV system can represent a systemic risk. With a through analysis of the current accidents to date and an understandings of the fundamentals of AV systems, this paper proposes three upgrades to this infrastructure. First, an updated "black box" and police accident report. Second, an escalation procedure depending on the diagnosis of the fault, and finally a database scheme to enable ongoing learning to find systemic issues.

VI. Future Work

To date, the AMI team has built a baseline infrastructure. Next steps are to enrich the accident database, build an executable AV vehicle accident report, and a learning engine for ongoing learning. On the database, we plan on mining information from other databases such as NOAA (weather) or Florida traveller information (traffic conditions) to enrich the data. We have built a version of AV vehicle accident report and we plan on engaging with Florida Law enforcement to integrate it into their flow. Finally, we are building capability to take existing accidents and automatically build capabilities to recreate the accident in our simulation framework.

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