DATA REQUIREMENTS FOR POST-CRASH ANALYSES OF COLLISIONS INVOLVING COLLISION AVOIDANCE TECHNOLOGY EQUIPPED, AUTOMATED, AND CONNECTED VEHICLES

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ABSTRACT

Crash causation studies that stretch back to the 1960s have consistently reported human (primarily driver) errors as the cause of the overwhelming proportion of roadway collisions. Application of driver alert and active collision avoidance technologies may begin to affect drivers' pre-collision actions and their resultant success in crash avoidance or injury mitigation when a crash does occur. With the introduction of connected vehicle (V2X) technologies, vehicle-to-vehicle communications will better inform drivers to take avoidance actions or in some cases even automatically control the longitudinal and lateral dynamics of the vehicle so as to avoid collisions and mitigate injury should a crash occur regardless. Further, the great promise of automated[1] vehicle systems is the elimination of most driver observational, judgement, and controls actuation errors, thus resulting in collision avoidance or in injury mitigation should a crash occur. Safety researchers anticipate that these systems now emerging as new safety technologies, or currently in advanced research stages will provide significant public health benefits but may not prove to be one hundred percent effective in collision avoidance.

The sensor inputs, controls algorithms, and driver alerts and/or vehicle systems actuations that may be commanded by Advanced Driver Assist systems or by various levels or automated driving systems are engineered parameters and will be well understood at introduction of the systems into the stream of commerce. However, as vehicles equipped with advanced collision avoidance technologies and automated driving systems are anticipated to continue to be involved in some crashes, it is essential that safety researchers, engineers, and regulators are able to develop a complete understanding of those collisions that continue to occur and why such collisions did occur. Conventional accident reconstruction techniques will be insufficient to the task of understanding pre-crash conditions, changes in conditions observed prior to impact, and post-impact events. Therefore, research demands for data related to prevailing conditions, conditional awareness, and post-crash data availability are critical to development of

[1] The authors use the term "automated" in a context synonymous with "autonomous", "self-driving", "driverless", "unmanned", and "robotic" vehicle control systems. Safety researchers, vehicle engineers, and regulators have used all of these terms and other shorthand titles to characterize a vehicle that to one degree or another perform part of the "dynamic driving task". Our use of "automated" is consistent with SAE J3016. Herein after, we will use: automated driving system or Automated Vehicles (AV) to refer to such vehicle systems.

understanding of crash causation and further refinement of safety systems through study of customer use experiences. This paper introduces some criteria for selection of pre-crash, collision, and post-crash related data that may be of use in understanding crash causation in advanced crash avoidance platforms and in engineering refinements in second and subsequent generations of advanced collision avoidance technologies including automated driving system equipped vehicles.

BACKGROUND

Event Data Recorders (EDRs) have been applied in light-duty passenger vehicles for over 40 years (DOT HS 810 935, 2008). Registration of some collision dynamic parameters in the airbag control module to control and record air bag deployment conditions was a feature implemented in the earliest air bag systems deployed by the General Motors Corporation(GM) in a 1000 vehicle test fleet in 1973 and in certain production model vehicles in 1974 (DOT HS 810 935, 2008). GM has used the term sensing and diagnostic module (SDM) to identify many of its early air bag control modules. With model year 1994, GM made SDM data publically accessible in some Chevrolet, Cadillac, and Buick models so as to increase accessibility to safety researchers (Parker, 2016).

These early generation EDRs documented limited vehicle parameters: air bag deployment timing, supplemental inflatable restraint (SIR) warning lamp status (on/off), vehicle longitudinal acceleration, driver seat belt status (buckled/unbuckled) for the specific crash involved vehicle, and certain circumstantial conditions of the vehicle sensors necessary to the triggering event. Crash pulse recording duration in the early generation EDRs is commonly 100-150 ms, however some record for as little as 70 ms or as much as 300 ms (Niehoff, 2005). Change in vehicle velocity (delta-v) was reported based upon integration of accelerometer output.

Beginning in 1997, GM engineered a new EDR system and after a test fleet trial during calendar year 1998, introduced a new generation of SDMs by adding recording and storage of basic pre-crash information (Lawrence, 2003) for some of the 1999 model year new car fleet. This new element of the SDM was named the Event Data Recorder (EDR) and was intended for use in safety research projects to better understand pre-crash vehicle performance, certain driver actions, and resultant collision dynamics. GM engineered a pre-crash recording duration of 5 seconds limited by the amount of data that could be embedded in the RAM recirculating buffer of a then existing SDM unit. It was an opportunistic usage of available capacity.

Early EDRs of the GM type that record pre-crash data generally capture: vehicle speed, engine RPM, percent throttle, and service brake switch circuit status. More recent EDRs may also record accelerator pedal position, transmission gear range status, ABS activity, stability control activity, traction control activity, yaw rate, steering wheel angle, individual wheel speed, cruise control status, and other parameters. Time-of-crash data can include passenger seat occupancy, driver's seat position, ignition cycles at deployment, diagnostic trouble codes at event, low tire pressure warning status, remote start status, service engine status, and door ajar status. Often, multiple events can be recorded, typically two or three, and the event order and time between events is reported. Advances in restraint systems have resulted in placement of

additional airbags within the occupant compartment, side impact airbags, head protection side impact air bags, rollover roof mounted air bags, and knee air bags.

Application of side impact air bags required additional collision sensors that are engineered to identify side impact or imminent rollover and command deployment of the appropriate air bag.

The development of rollover sensing technology is described in "Rollover Sensor Signature Test Development, SAE 2007-01-0375", O'Brien-Mitchell et.al.; "Ejection Mitigation in Rollover Events – Component Test Development, SAE 2007-01-0374", O'Brian-Mitchell and Lange; and "Data Analysis Methodology and Observations from Rollover Sensor Development Tests, ESV 07- 0308", O'Brian-Mitchell et. al. and is not included here in the interest of brevity.

NHTSA began working with automotive manufactures in the 1990s to promulgate an EDR rule as a safety technology useful to safety researchers and common in content across automotive manufacturers and Tier 1 suppliers that applied EDR technology. On June 14, 2004, NHTSA issued a Notice of Proposed Rulemaking (49 CFR Part 563 Docket No. NHTSA-2004-18029), recommending that EDRs record a specific set of vehicle-centric parameters. On August 28, 2006, NHTSA issued a final rule for EDRs in vehicles manufactured after September 1, 2012 [49 CFR 563 Docket No. NHTSA-2006-25666]. The regulation commonized the required: content for EDRs when vehicles were so equipped and that the data be publicly accessible with commercially available tools. On January 14, 2008, NHTSA issued its response to petitions for reconsideration regarding the EDR Final Rule (49 CFR 563 Docket No. NHTSA-2008-0004). A timeline of historic EDR events is illustrated in Figure 1.

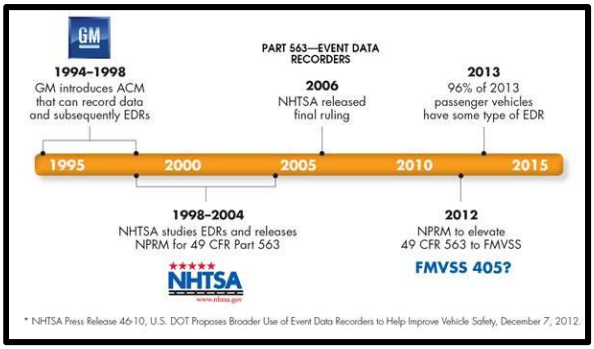

Figure 1. Timeline of EDR evolution.

EDR application into light duty vehicles that enabled access to recorded data increased subsequent to NHTSA's rulemaking. In model year 2005, approximately 64% of light duty passenger vehicles were equipped with an EDR (NHTSA, Event Data Recorders, Final Rule, 49 CFR 563 Docket No. NHTSA-2006-25666), and by model year 2013, the proportion had risen to approximately 96% (NHTSA Press Release 46-10).

A crash investigator can download EDR data using commercially available tools. Bosch produces the Crash Data Retrieval (CDR) system, which allows trained investigators to download EDR data from vehicles as old as 1994 for selected GM models (Wilkinson et al., 2008 09B-0348). The range has since expanded to include most major domestic and foreign brands.

History of Crash Causation

Motor vehicle safety researchers began to study crash causation early in the development of motor vehicle safety science. By the mid-1970s, NHTSA had contracted for, and was publishing data and analyses regarding crash causation to enable consideration and development of countermeasures to prevent roadway crashes

or to mitigate the effects of crashes when they occur. (Reference: "Tri-level Study of the Causes of Traffic Accidents: Final Report.) In those initial studies and throughout, to more current studies of crash causation (Reference: "National Motor Vehicle Crash Causation Survey, DOT HS 811 059", July 2008.) human errors of various types have been identified as cause of more than 90% of crashes on U.S. roadways. This fact and technology developments in computing capacity and sensor capabilities have emboldened safety researchers and engineers to propose safety countermeasures that remove responsibility and authority from a human driver for: monitoring and processing instantaneous roadway circumstantial conditions; instituting appropriate control responses to those circumstantial conditions; scanning for looming collision threats and adjusting control settings and actions to avoid collisions or mitigate collision severity should avoidance be impossible in the time from recognition to collision. Those safety countermeasures are characterized as automated vehicles: wheeled ground vehicles with the capacity to replace the human driver in execution of some or all driving tasks during a trip.

Definition of Automated Driving

As there are expectations that automated vehicles are being, and will continue to be, developed with a range of capabilities and capacities, it has been necessary to develop a vocabulary to characterize automated vehicle performance and to differentiate levels of control that users and riders may reasonably expect from the technology. The SAE has established such a vocabulary for use in this developing scientific domain; that is SAE International "Surface Vehicle Recommended Practice J3016, SEP2016, Taxonomy and Definitions for Terms Related to Driving Automation Systems for On-Road Motor Vehicles" revised 2016-09.

SAE J3016 provides a "Rationale: This Recommended Practice provides a taxonomy describing the full range of levels of driving automation in on-road motor vehicles and includes functional definitions for advanced levels of driving automation and related terms and definitions". Some terms necessary for understanding are:

1. Dynamic Driving Task (DDT) – "All of the real-time operational and tactical functions required to operate a vehicle in on-road traffic, excluding the strategic functions such as trip scheduling and selection of destinations and waypoints….." (ibid, "Definitions", page 5.)
2. Operational Design Domain (ODD) – "The specific conditions under which a given driving automation system or feature thereof is designed to function, including, but not limited to, driving modes. (ibid, "Definitions", page 3.)
3. Active Safety System (SAE J3063:NOV2015) – "Active safety systems are vehicle systems that sense and monitor conditions inside and outside the vehicle for the purpose of identifying perceived present and potential dangers to the vehicle, occupants, and/or other road users, and automatically intervene to help avoid or mitigate potential collisions…" (ibid, "Definitions", page 12.)
4. Automated Driving System (ADS) – "The hardware and software that are collectively capable of performing the entire DDT on a sustained basis, regardless of whether it is limited to a specific operational design domain (ODD)…." (ibid, "Definitions", page 3.)
5. Driving Automation System or Technology – "The hardware and software that are collectively capable of performing part or all of the DDT on a sustained basis;…." (ibid, "Definitions", page 3.)
6. Driving Mode – "A type of vehicle operation with characteristic DDT requirements (e.g., expressway merging, high-speed cruising, low-speed traffic jam, etc.). (ibid, "Definitions", page 5.)
7. Dynamic Driving Task (DDT) Fallback – "The response by the user or by an ADS to either

perform the DDT or achieve a minimal risk condition after occurrence of a DDT performance-relevant system failure(s) or upon ODD exit. (ibid, "Definitions", page 5.)

8. DDT Performance-Relevant System Failure – "A malfunction in a driving automation system and/or other vehicle system that prevents the driving automation system from reliably sustaining DDT performance (partial or complete)." (ibid, "Definitions", page 10.)
9. Monitor – "A general term referencing a range of functions involving real-time human or machine sensing and processing of data used to operate a vehicle, or to support its operation. (ibid, "Definitions", page 10.)
10. Monitor the Driving Environment – "The activities and/or automated routines that accomplish real-time roadway environmental object and event detection, recognition, classification, and response preparation (excluding actual response), as needed to operate a vehicle. (ibid, "Definitions", page 11.)
11. Object and Event Detection and Response (OEDR) – "The subtasks of the DDT that include monitoring the driving environment (detecting, recognizing, and classifying objects and events and preparing to respond as needed) and executing an appropriate response to such objects and events (i.e., as needed to complete the DDT and/or DDT fallback)." (ibid, "Definitions", page 12.)
12. Request to Intervene – "Notification by an ADS to a driver indicating that s/he should promptly perform the DDT fallback. (ibid, "Definitions", page 13.)
13. Supervise (Driving Automation System Performance) – " The driver activities, performed while operating a vehicle with an engaged level 1 or 2 driving automation system, to monitor the driving automation system's performance, respond to inappropriate actions taken by that system, and to otherwise complete the DDT. (ibid, "Definitions", page 13.)
14. Sustained (Operation of a Vehicle) – "Performance of part or all of the DDT both between and across external events, including responding to external events and continuing performance of part or all of the DDT in the absence of external events." (ibid, "Definitions", page 13.)

SAE J3016 categorizes driver assist and automated driving systems into six levels of increasing machine interactions with a human driver or control based upon five considerations:

1. Does a driving automation system control longitudinal or the lateral motion in the "Dynamic Driving Task"?
2. Does the driving automation system control both longitudinal and the vehicle motion "Dynamic Driving Task" simultaneously?
3. Does the driving automation system also control "Object and Event Detection and Response"?
4. Does the driving automation system also provide fallback control in the "Dynamic Driving Task" in the event of malfunction, anomalous performance, of failure?
5. Is the driving automation system limited to select "Operational Design Domains"?

Based upon these criteria, levels 0 through 5 are defined as listed SAE J3016. SAE J3016 differentiates automated driving levels from driver assist features that are increasing in application to the new car fleet currently. Levels 1 and 2 involve driver assist technologies, those functions may extend to higher levels as well. Levels 4 and 5 provide an automated driving system capable of functioning without human supervisory control, at least in some operating domains. Level 3 provides automated functions under human monitoring where a driver is required to be ready to receive control from the automated driving system should it encounter circumstantial conditions it cannot navigate.

Application and integration of automated vehicles (AV) in small numbers, hundreds of vehicles, has been initiated by various institutions active in the domain: Google (now Waymo), Cruise Automation (now part of General Motors), Uber (and Otto, an acquired AV firm) have been operating individual vehicles or fleets of vehicles in testing and on public roadways for several years. Conventional vehicle manufacturers (Tesla, Audi, and Volvo

for example) have also demonstrated AV function on public roadways. As applications are increasing, governmental agencies responsible for roadway infrastructure use and safety have undertaken consideration of enabling or limiting legislation, guidance, and regulation governing AV applications on public roadways. Some jurisdictions have acted to adopt new rules to govern AV applications. As motor vehicle regulation is a distributed responsibility, AV providers will have to interact with regulators at the local, State and federal levels.

The non-profit "Securing America's Future Energy" (SAFE) has issued a report and recommendations for AV providers during the development and early applications of AV technologies. The report is entitled: "Commission on Autonomous Vehicle Testing and Safety, A project of Securing America's Future Energy" and is dated January 5, 2017. That report described the regulatory challenge to adoption of AV technologies as follows: "Regulation of emerging technology is always challenging, but autonomous vehicles face two exceptional obstacles. The first is that vehicles are regulated by a complex network of national, state, and local laws. The second is that AVs function based on highly sophisticated computer algorithms, or software. These technologies stress current regulatory frameworks, which are designed to test and approve more limited safety technologies such as seatbelts, airbags, or basic collision warning systems. The broad deployment of AVs will depend on finding new approaches to the verification and certification of safety."

"Safety assurance will present a challenge to regulators and create a major roadblock in the regulatory process. Manufacturers must not only achieve an acceptable level of safety, but also convince regulators, users, and the public at large." (Reference: "Commission on Autonomous Vehicle Testing and Safety, A project of Securing America's Future Energy", January 5, 2017, page 9.)

AV system providers will face and address multiple regulatory challenges during testing and early deployment of AV systems and the National Highway Traffic Safety Administration (NHTSA) has been proactive in trying to provide regulatory certainty in an uncertain and fast changing technology domain. The SAFE Commission remarked upon this fact as well: "The Commission also urges AV providers to keep relevant regulatory bodies apprised of their progress and intention to test or deploy AVs on public roads. This is consistent with NHTSA's Federal Automated Vehicles Policy, which requests, voluntarily, 4 months advance notice before active public road testing begins on a new automated feature. Ideally, state and local authorities should be engaged and kept abreast of provider intentions in order to facilitate local acceptance." (ibid, page 10.)

NHTSA published "Federal Automated Vehicles Policy, Accelerating the Next Revolution in Roadway Safety" in September of 2016. NHTSA sees AV systems as a potential safety benefit of significant proportion (Reference: "Federal Automated Vehicles Policy", page 5.) NHTSA wrote: "Recognizing this great potential, this Policy sets out an ambitious approach to accelerate the HAV revolution. The remarkable speed with which increasingly complex HAVs are evolving challenges DOT to take new approaches that ensure these technologies are safely introduced (i.e., do not introduce significant new safety risks), provide safety benefits today, and achieve their full safety potential in the future. To meet this challenge, we must rapidly build our expertise and

knowledge to keep pace with developments, expand our regulatory capability, and increase our speed of execution." (ibid, page 6).

"This Policy is an important early step in that effort. We are issuing this Policy as agency guidance rather than in a rulemaking in order to speed the delivery of an initial regulatory framework and best practices to guide manufacturers and other entities in the safe design, development, testing, and deployment of HAVs" (ibid, page 6.) NHTSA's use of the term "HAVs" refers to "Highly Autonomous Vehicles", levels 4 and 5 in SAE J3016.

TECHNOLOGY CONTENT FOR AUTOMATED VEHICLES

According to The Insurance Institute for Highway Safety, full deployment of crash avoidance features could prevent 1.9 million crashes per year of which 10,000 would be fatal crashes (IIHS, 2010).

In addition to their role in crash avoidance, the technology used in automated vehicles and advanced driver assistance systems will sense and record data that is useful in later determining the position, velocity, and heading of all roadway users involved in a crash, including vehicles, pedestrians, cyclists, and objects. These data will be useful to manufacturers, regulators, and investigators in in determining crash causation and learning how these systems work and interact with humans and the driving environment.

Automated driving systems operation and driver warning systems include a network of sensors, actuators, and computer processing to interpret and provide notice to human drivers or in the case of automated driving systems, actually control the vehicle performance throughout some or the entire dynamic driving domain. A potential obstacle to effective operation of automated driving and crash avoidance features is loss of data from one or more sensors. Other issues: false signals from other vehicles, signal interference from localized signal saturation, malicious sensor spoofing, or sensor malfunction could potentially challenge the system's capacity to collect and process data to issue the appropriate notice or control commands. Sensor fusion, hardware and software redundancy, and V2X capability may offer potential solutions to such challenges. Sensor loss and other signal challenges impose burdens upon automated systems and will likely also complicate post-crash data analysis in the event of a collision consequent to the loss of system integrity regardless of cause or source.

We know that human distraction and/or impairment degrade drivers' abilities to safely navigate, observe, cognitively process, and actuate control actions appropriate to the surrounding circumstances. Difficult driving situations present challenges to both human drivers and automated vehicles, as do complex driving environments involving other roadway users and multiple simultaneous potential looming collision threats. AVs are potentially advantaged in an ability to utilize parallel sensor data so as to manage difficult driving scenarios; for instance, infrared cameras can detect pedestrians in dark areas, and LiDAR can offer a 360-degree view around the vehicle.

Vehicle safety technologies have contributed to the reduction of crash-related injuries and deaths (IIHS, 2012). Adoption of safety features has been deliberate and steady. Typically available in a few new car models at technology introduction, with some trim levels providing the new technology as standard equipment.

Successful technologies may reach a 50% adoption rate in a new car fleet in a decade or so (Reference: “Installation Patterns for Emerging Injury Mitigation Technologies, 1998 Through 2010, ESV 11-0088”, Lange et. al). Some technologies that may provide a safety benefit may have longer latency periods. The hardware, processors, and software necessary for function of automated vehicle systems and advanced driver warning systems may include but are not limited to:

Light Detection and Ranging (LiDAR) systems (Texas Instruments, 2011, Ibeo, 2017). LiDAR systems operate in all lighting conditions; (Wilkinson, 2017) but may experience degraded performance or false signals due to scattering in rain, fog, or snow, as well as reflective objects (Rasshoder 2011). LiDAR systems generate a “point cloud” , identifying the spatial position of all detected objects in the field of view (Velodyne, 2013).

Radio Detection and Ranging (RADAR) systems emit radio waves that reflect off objects and return to a sensor that determines the range and velocity of these objects (Delphi, 2017, Bosch, 2015, Batsch, 2012.) Modern automotive RADAR operates in the 200-foot range from the sensor. Rear-facing radar with a wider field of view is often used in blind spot monitoring application.

Sonic Ranging (SONAR) emits sound waves that reflect off objects and return to a sensor that can determine range and velocity of these objects.

Stereoscopic video for object detection provides data regarding location and shape. Generally it will not function in low or no light conditions or certain bright light conditions.

Global Positioning System (GPS) is satellite-based geolocation with an accuracy of 8m (NOAA, 2017), that can be increased up to the centimeter level through the use of various base augmentation systems.

Inertial Measurement Units (IMUs) are used to determine acceleration and attitude of the vehicle. They are also commonly used in Anti-lock Braking Systems, active suspension, and airbag deployment modules.

Infrared (IR) cameras detect the thermal signature of objects and deliver an image array to the processor. Since IR does not need visible light to detect objects, it is used for night vision and pedestrian detection systems (FLIR, 2017 and Sensors Unlimited, 2017).

Wheel Speed sensors measure the rotational speed of a wheel or axle. ABS and Electronic Stability Control (ESS) systems use wheel speed sensors to determine if one or more wheels have lost traction and together with IMUs and GPS to provide inertial navigation.

V2X Transceivers will exchange data with other vehicles, other roadway users (pedestrians, pedi-cyclysts, motorcyclists) and infrastructure elements (NHTSA, 2017 (Reference SAE /j2735_200911).

After a crash, data from the EDR of multiple vehicles may be compared with other observations by the investigators to recreate the circumstances that led to the accident. In order to quantitatively compare data from multiple sensors systems and from different vehicles, an absolute clock basis such as GPS time will be useful.

GPS spoofing and other malevolent interference with an AV system are concerns for potential causation and ultimate understanding of a crash

scenario. Sensor fusion or another clock basis for the sensor systems may be useful to offer redundancy in time synchronization.

Functional Safety Requirements

Functional safety, the absence of unacceptable risk due to hazards stemming from component or system failures, is imperative to safety-critical control systems. The complex nature of today's electro-mechanical and software control systems used in automotive systems, especially those required for automated vehicle operation, require in-depth safety assessments and the application of safety standards; ISO 26262 Road Vehicles – Functional Safety is such a standard. Released in November 2011, ISO 26262 "…is intended to be applied to safety-related systems that include one or more electrical and/or electronic (E/E) systems and that are installed in series production passenger cars with a maximum gross vehicle mass up to 3 500 kg." (ISO26262, 2011) In addition to ISO 26262, there are other safety standards and systems engineering processes and principals that will be employed for safety engineering. As automated vehicle systems, software, and components increase in complexity, the application of functional safety standards and requirements are be critical to the safe deployment of software controlled systems.

Systems Redundancy

Processing data from multiple sensors reduces uncertainty of the estimate of the state of the system or vehicle and increases the accuracy and integrity of the estimate. A reliable automated vehicle must be able to gracefully accommodate loss of data, false signals, or reduced fidelity from one or more sensors; sensor fusion can potentially provide solution sets for partial disable conditions. Mechanical damage or optical interference to the sensors are possible causes of sensor loss, as are intentional actions such as sensor spoofing or some unintentional actions such as vehicular crosstalk (Lundquist, 2011).

Several redundancy schemes are available for mitigating sensor performance degradation. Sensor fusion is an example of redundancies that does not duplicate sensor coverage, but rather exploits the strengths of multiple sensors. A typical setup for automated emergency braking systems is the combination (i.e., fusion) of RADAR and an optical camera. RADAR has better visibility in fog or rain than a camera, but cannot determine shape or color of roadway markings or signage.

Sensor fusion also offers a potential fallback in the event of sensor data loss. For example, if the front-facing radar used for adaptive cruise control is damaged, data from LiDAR or an optical camera can be supplemented to determine the distance and speed of objects in front of the vehicle and possibly continue to provide undiminished or at least sufficient functions for continued application. Failure to maintain full function requires backstop solutions.

Communication between multiple vehicles on the roadway and between vehicles and infrastructure can supplement for sensor data loss. Broadcasting traffic information can accommodate for reduced visibility of a LiDAR system in conditions such as fog or snow. By communicating traffic and environmental observations from vehicle to vehicle or between vehicle and infrastructure, this type of redundancy can effectively reduce or compensate for the potential adverse effects of the lack of sensor data on one vehicle by

supplementing that data from other vehicles' sensor systems (NHTSA, 2017).

EDR FUNCTIONS FOR AUTOMATED VEHICLES

There are numerous considerations in selecting an appropriate time period for event data recording for ADAS-equipped and automated vehicles involved in crashes. The sections below discuss some of these considerations aimed at collecting data to understand what happened in the crash so as to enable safety researchers and engineers to generate a path of continuous improvement in systems functions and safety performance.

ADAS-equipped and automated vehicles are expected to operate in all environmental conditions including rain, fog, and snow. Not only do these conditions challenge the perception sensors on these vehicles, but they may modify the timescale of the vehicle dynamics through the available road friction to the vehicle (for example, time from braking actuation to final rest), and therefore the anticipated time period for data recording.

ADAS-equipped and automated vehicles will operate in both urban and rural environments where the density of vehicles, pedestrians, bicyclists, and other moving and fixed objects will vary. As such, the expected travel speeds, vehicle to fixed and moving object distances, and number of tracked objects will vary greatly. Driver-assisted and automated vehicles will still be involved in some collisions. It is difficult to anticipate all potential crash scenarios and the time period for data recording necessary to fully document the relevant pre-crash conditions vary.

As a potential bounding exercise consider a high speed loss of control scenario in which an AV is traveling at 85 mph, slides on an unanticipated low friction patch of roadway, departs the road, and impacts a tree at 20 mph. Assuming a dynamic friction coefficient of 0.2, the sliding distance and time are approximately 1140 ft and 15 seconds, given by:

$$d = \frac{v_i^2 - v_f^2}{2a} \qquad \text{(Equation 1)}$$

$$t = v_i - v_f \setminus a \qquad \text{(Equation 2)}$$

Where v_i is the initial velocity, v_f is the final velocity, a is the acceleration, d is the distance, and t is the time. This exercise suggests an upper limit of as much as 15 seconds for AV system EDR function so long as any security breach is permanently registered at occurrence and notice provide to a supervisory authority. It should be noted that any effort to specify pre-crash recording timing should also consider the frequency of the crash mode considered, the injury potential, and the implementation cost on a large scale.

ADAS-equipped and highly automated vehicles (HAV) utilize exteroceptive sensors to continuously monitor and characterize the developing roadway environment, and generating data that is processed and applied in decision-making algorithms to determine: the path and motion of the vehicle, surrounding object occurrences and motions, to identify looming collision threats, and to effect appropriate control responses. Therefore, to comprehensively evaluate vehicle performance post collision, three categories of data elements must be considered: sensor data, classification data, and decisional data. It is especially important to record critical elements of all three data elements to understand the motion and behavior of the vehicle with respect to the surrounding environment prior to the crash.

Exteroceptive sensors including LiDAR, RADAR, IR, and visual imaging, can generate significant amounts of data, both raw and post-processing.

For example, a LiDAR could report a point cloud (raw) or a simplified geometrical description of a classified object type (highly processed). In the former, point clouds of LiDAR data may require substantial storage requirements on a data recorder, while a basic geometric description of a detected object type may require relatively little. It is appropriate and desirable to record both types of input data and the data that was issued as responsive control commands. The EDRs will also have to register malevolent interference, sensor saturation, and any failure in system health, system readiness, and electrical continuity. Recent transmissions of V2X data and recent reception of paired data packets will also have to be registered within the EDR system.

EDRs for HAVs include information regarding how the vehicle classified and interpreted the world. Classification data elements can include highly-processed data elements that describe how the vehicle perceived and recognized the world (including how the vehicle was positioned with respect to the map). These data elements can be similar in nature to the sensor data elements but will only include the data that the vehicle utilized in the decision process.

Decisional data elements include information regarding what the vehicle processors commanded in terms of control actuation in advance of the crash. A highly automated vehicle has to plan a path and impart appropriate driving inputs to follow that path using a combination of actuators (similar to what human drivers do). Therefore, decisional data elements will include the planned trajectory as well as accelerator, braking, and steering commands effected to generate the desired path. Collecting such actuator data for HAVs will be highly useful to understand if the vehicle's performance and motion was consistent with its intended path, providing a more complete characterization of the automated vehicle situational awareness in pre-crash conditions, processing output, control commands, and final outcome.

CONCLUSIONS

Driver assist technologies function so as to alert drivers to looming collision threat and (generally) require driver initiated control actions necessary to avoid or mitigate that looming collision threat. Proper awareness and reaction to the alert is, in general dependent upon driver recognition, cognitive processing for reaction, and appropriate control actuation. Responsibility and authority rests with the human driver. However, driver recognition is to some degree dependent upon timely delivery of notice to looming collision threats; system failures or malfunctions, edge case performance anomalies; malevolent interference; or sensor overload. Should any of these conditions obtain prior to actuation of the appropriate driver alert, the system may fail in timely delivery. The prevailing operating conditions that precede a collision (including system readiness, data and data processing), whether an appropriate notice had been issued or not, will need to be registered in an EDR and available to enable safety researchers to attribute causation and engineering of corrective actions where necessary.

Automatic Emergency Braking operates a little differently in that should the driver not properly react in advance of reaching the time to collision (TTC) critical to avoidance; sensor data, processing, and control actuation authority will be assumed by the system and braking actuation will initiate absent any driver action. However, system failures or malfunctions; edge case performance anomalies; malevolent interference; or sensor overload may prevent proper system function. In all collision occurrences, the prevailing operating conditions that precede a

collision (including system readiness, data and data processing), whether an appropriate control action had been issued or not, will need to be registered in an EDR and available to enable safety researchers to attribute causation and engineering of corrective actions where necessary.

Automated vehicles at levels 3, 4 and 5 to some degree or fully assume observational responsibility and control authority from the human driver and exercise those responsibilities and authorities through the AV system. System failures or malfunctions; edge case performance anomalies; malevolent interference; or sensor overload may prevent proper AV system function. In all collision occurrences, the prevailing operating conditions that precede a collision (including system readiness, data and data processing), whether an appropriate control action had been issued or not, will need to be registered in an EDR and available to enable safety researchers to attribute causation and engineering of corrective actions where necessary.

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