A SURVEY OF ELECTRICAL AND ELECTRONIC (E/E) NOTIFICATIONS FOR MOTOR VEHICLES

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ABSTRACT
Modern motor vehicles are becoming increasingly dominated by electrical and electronics (E/E) systems. While this trend is clear, its implications are uncertain. In this paper, we investigate data on safety-related notifications from the United States, Canada, and Europe to analyze questions and trends related to E/E systems. The data analysis indicates that E/E systems are a growing issue for motor vehicle safety, that the time delay for E/E notifications is longer than that for other notifications, and that specific subsystems are more prone to E/E problems than others.

1 INTRODUCTION

Modern motor vehicles are complex safety-critical systems that involve the coordination of dozens of computers, communication buses, actuators, and sensors [1, 2]. Their overall functionality and safety is dependent upon the correct and timely operation of electronics and software to sense and control physical states through sensors and actuators. Table 1 reports estimated numbers of ECUs (electronic control units; the usual term used for computers in cars) in recent model year vehicles and literature sources for these estimates. With approximately 50 to 75 ECUs, modern cars are truly distributed computer systems running on wheels.

Since motor vehicles are safety-critical systems, countries developed safety standards to protect consumers and the public. Regulatory standards such as the Federal Motor Vehicle Safety Standards and Regulations (FMVSS) [3] of the United States Department of Transportation (USDOT) codify required safety systems, their performance, and overall vehicle safety. For example, FMVSS Standard No. 126 governs electronic stability control (ESC) systems and includes the following requirement [3, Standard No. 126, § 5.1.1]: *"Is capable of applying brake torques individually to all four wheels and has a control algorithm that utilizes this capability."* Some countries have dedicated mandatory standards for tire safety. In addition to these regulatory standards on vehicle safety, the industry voluntarily has also created and uses domain-specific standards. For example the ISO 26262 [4] standard on *Road Vehicles: Functional Safety* is used for developing, maintaining, and decommissioning automotive components. The MISRA C [5] standard provides guidelines for source code in safety-critical applications using C and C++. Unlike FMVSS, complying with the ISO 26262 or MISRA C is optional.

Each country instated a regulatory agency in conjunction with these standards. These regulatory agencies police the mandatory safety standards and notify the public about non-compliance and safety-related concerns for products sold in their jurisdiction. In the United States, the National Highway Traffic Safety Administration (NHTSA) regulates vehicle safety through standards like the FMVSS. In Canada, Transport Canada is responsible for transportation policies and programs such as the *Motor Vehicle Safety Regulations* [6] and related acts. In the European Union (EU), the European Commission and member countries are jointly responsible for safety regulations such as the *General Safety Regulation* [7] and related laws. In addition, the European Commission administers the Rapid Alert System for non-food dangerous products (RAPEX) to facilitate the rapid exchange of information to the consumer on safety-related issues.

Each of these agencies maintains datasets (databases) on automotive safety notifications, potential hazards arising from the issues, and recommended corrective actions. Notifications in the datasets concern

Year	List of: Vehicle (ECUs) [Source]
2004	VW Phaeton (61) [8], Current Upper Class (70) [9]
2005	Volvo cars (40) [10]
2006	Infiniti (11) [11], Toyota Prius (23) [11]
2007	Current Premium Car (70) [12]
2009	Current Premium Car (70-100) [13], Current Low-end Car (30-50) [13], Average Car (30-45) [14], Luxury Cars (70) [14]
2010	Jeep (7) [11], Range Rover (41) [11], Basic vehicles (30) [15], Some Luxury Cars (100) [15]
2012	Most new vehicles (100) [16]
2014	Infiniti (34) [11], Dodge Viper (19) [11], Range Rover (98) [11], Jeep (17) [11], Toyota Prius (40) [11], Average Vehicle (60) [17]

Table 1: Reported and estimated numbers of ECUs in cars. *"Year"* is the year of reporting.

hazards and risks when operating motor vehicles, particularly as they pertain to non-compliance with standards like FMVSS. For instance, the purpose of the FMVSS ESC standard mentioned previously is *"...to reduce the number of deaths and injuries that result from crashes in which the driver loses directional control of the vehicle, including those resulting in vehicle rollover"* [3, Standard No. 126, § 2]. A malfunctioning component used in the ESC would then raise a hazard and thus a safety concern. A *hazard* is the possibility of suffering harm or injury of road participants (users). Road participants include, for instance, the driver, passengers, but also extends to pedestrians and cyclists. A hazard by itself is sufficient to cause an investigation; for example, the NHTSA may start an investigation upon receiving complaints from owners about defects. The level of risk of the hazard occurring during driving is a key element, with a *risk* being a situation that involves exposure to danger. There are many dangers present in the operation of motor vehicles, such as injuries due to collisions with other vehicles or objects, or burns due to engine fires or seat heater failures. Often a defect in the design or the implementation of a safety-related system in the motor vehicle will create an unanticipated risk that needs to be investigated. A safety-related *defect* in a motor vehicle or system thereof exists when there is increased risk beyond an acceptable level. In this situation, the defect causes the system to become unsafe and consequently corrective actions have to be taken, together with a notification of the public through the regulatory agency.

This paper presents an analysis of electrical and electronic (E/E) notification datasets from government regulatory agencies in the United States, Canada, and Europe. Since E/E encompasses software, notifications related to software are also part of our analysis. With this data, we explored several questions, such as the trend of E/E notifications over time in terms of the number of notifications and affected vehicles. We also analyzed E/E notifications in relation to Non-E/E notifications, and investigated the risk types associated with defects and the relationship between notifications and the model year for E/E vs. Non-E/E notifications. The paper concludes with additional observations made during the analysis and provides a call-to-action for researchers, the regulatory agencies, and also the automotive industry.

2 METHODS AND DATA SOURCES

This paper analyzes safety notification datasets from several data sources of regulatory agencies. The main aim of the study is to determine the prevalence and quantity of E/E notifications and compare them to Non-E/E notifications. To this end, we analyzed data from the NHTSA, Transport Canada, and RAPEX. These datasets are publicly available and provide a rich and diverse view into the nature of safety-related notifications and recalls in the three jurisdictions (the US, Canada, and Europe).

2.1 E/E Systems, Defects, and Notifications

We define our terminology following the vocabulary used in the ISO 26262 standard [4]. ISO 26262 is a comprehensive standard on functional safety of components (i.e., items) built into road vehicles.

We analyze datasets from three data sources: *"Complaints, Defect Investigations, Recalls, & Technical Service Bulletins"* (NHTSA) [18], *"Road Safety Recalls Database"* (Transport Canada) [19], and *"Rapid Alert System for non-food dangerous products"* (RAPEX) [20]. Each data source provides a dataset containing notifications. A *notification* is an entry that results from the process associated with the dataset. Each data source follows a different process for adding notifications to its datasets. Consequently a notification can be a compulsory recall, but it can also just be a benign complaint that led to an investigation, and ended in

Data Source	Dataset	Contents	No. Entries	Model Years	Access Date	Source
NHTSA	*"Recalls"*	Vehicle safety recalls	108 686 (18 768)	1960–2015	FEB-2015	[21, 18]
Transport Canada	*"Road Safety Recalls Database"*	Vehicle safety recalls	10 596	1970–2015	JAN-2015	[19]
European RAPEX	*"Rapid Alert System for non-food dangerous products"*	*Motor vehicles* category in non-food dangerous products	1 246	2006–2015	FEB-2015	[20]

Table 2: Summary of the datasets analyzed including the information contained. The access date is the date the dataset was downloaded for the analysis in this paper. While the datasets may already (as of February 2015) contain information for 2016 model year vehicles, only up to model year 2015 were included in the analysis in this paper. The NHTSA number in parenthesis is the number of unique campaign numbers.

the voluntary action of a press release. Section 2.2 discusses the data sources and datasets in more detail.

Since this paper is concerned with E/E artifacts, we must distinguish between E/E and Non-E/E artifacts. The ISO 26262 standard specifies *item* as the highest-level artifact. An item is then realized in systems, which are further broken down into elements. To keep the paper accessible to the general reader and because notifications in the datasets are usually related to specific artifacts, we will mostly use the term system for these instead of a specific breakdown of item, system, or element as defined in the ISO 26262 standard. We call a notification an *E/E notification*, if the reason for the notification originates from an E/E system and is not of mechanical or chemical nature. The ISO standard defines an E/E system as one that includes electrical or electronic elements, including (software) programmable electronic elements. Example E/E systems include power supplies, sensors, and other input devices, communication paths, and actuators and other output devices. For example, an E/E notification would be one related to stalls in hybrid vehicles due to the control software overheating power transistors. All notifications related to other technology (as defined for term 1.84 ISO 26262) are *Non-E/E notifications*. For example, a holding bracket loosening due to improper mounting is a Non-E/E notification.

2.2 Data Sources and Datasets

In our analysis, we use several datasets from the NHTSA, Transport Canada, and RAPEX from Europe to classify E/E and Non-E/E notifications. Table 2 provides a summary of the datasets and their contained information.

2.2.1 Complaints, Defect Investigations, Recalls, & Technical Service Bulletins (NHTSA)

The NHTSA maintains extensive datasets of vehicle and system recalls and complaints online [18]. These are categorized into several major datasets including *"Complaints," "Defect Investigations," "Recalls," "Technical Service Bulletins"* [18, 21], as well as *"Foreign Campaigns"* [22]. The NHTSA is part of the US Department of Transportation, was established in 1970, and has a mission to reduce deaths, injuries, and economic losses arising out of motor vehicle crashes. As part of these responsibilities, the NHTSA sets and regulates safety performance standards for motor vehicles, such as through FMVSS [3], monitors and investigates consumer complaints regarding motor vehicles, and also conducts research on driver behavior and traffic safety, such as conducting crash tests [23].

The NHTSA maintains information about all safety-related defect and compliance campaigns that occur in all models of motor vehicles in the US starting from notifications made in the year 1967. Defects are defined in Section 1, and *compliance* means that a given motor vehicle and its systems comply with regulatory standards, such as FMVSS. A system is *non-compliant*, if it violates a regulatory standard, so non-compliance notifications correspond to violations of FMVSS and other regulations. As ISO 26262 is a voluntary standard, only federal regulations like FMVSS are considered in the definition of compliance. The dataset also contains information on model year vehicles before 1967, since defects reported in 1967 can affect older models. The NHTSA stores different categories of information in its *"Complaints"*, *"Defect Investigations"*, *"Recalls"*, and *"Service Bulletins"* datasets. Complaints are reports of problems from vehicle owners to the NHTSA, and are investigated by the NHTSA and tracked in an investigation dataset. Service bulletins are instructions from the manufacturer regarding how to correct defects. There is a process to be followed by a vehicle

owner to report problems with their vehicles. When there is a problem with their vehicle or equipment, the owner can file a complaint with the NHTSA, for example online at http://www.safercar.gov. As part of a complaint, the owner may provide the vehicle's VIN, the incident information including, if there was a crash, fire, injury, or fatality as a result of the incident, and other information. Complaints are entered into the NHTSA complaint dataset and will be used to determine, if a safety-related defect trend exists. These complaints are searchable on the NHTSA's website based on various criteria including the make, model, and year of the vehicle. Investigations are taken up by the NHTSA as a result of complaints by vehicle owners, and may result in a recall or other action if it is deemed necessary. The NHTSA also has the authority to fine automakers. Additionally, a manufacturer may notify the NHTSA of a potential defect, if they become aware of one, so the process of creating notifications may be driven either by the NHTSA or the manufacturer.

This paper uses the NHTSA *"Recalls"* dataset that contains all NHTSA safety-related defect and compliance campaigns since 1967 [21]. A *recall* is described [24] as: *"When a manufacturer or the National Highway Traffic Safety Administration determines that a car or item of motor vehicle equipment creates an unreasonable risk to safety or fails to meet minimum safety standards, the manufacturer is required to fix that car or equipment."* A manufacturer will have to rectify or replace parts, if the recall is a safety recall. The manufacturer will also have to inform the vehicle owner of the recall. More information about recalls and how they are notified and how to find if a particular vehicle is under recall or not are in the Vehicle Owners section [24]. The *"Recalls"* dataset consists of recall records. Information contained as part of a recall record includes the vehicle make, models, model years, component description, beginning and end dates of manufacturing, the potential number of affected vehicles, the date of notification to the owner, a defect summary, a consequence summary, a correction summary, and recall notes [18].

2.2.2 Road Safety Recalls Database (Transport Canada)

In Canada, transportation policies and programs are the responsibility of Transport Canada [25]. Transport Canada promotes safe, secure, efficient, and environmentally-responsible transportation. Transport Canada reports to Canadian Parliament and the Minister of Transport. Transport Canada administers various programs related to safety of vehicles such as importation of vehicles, advanced vehicle technologies, commercial vehicles, defect investigations, and vehicle recalls. The *"Road Safety Recalls Database"* in Canada is managed and maintained by Transport Canada. Transport Canada also documents recall campaigns, update the on-line recalls database, and monitor recall completion rates. Each record in the dataset contains the date of recall, make, model, system, model year(s) affected, recall details, category of the vehicle, etc. [19]. The records start from 1970 model year vehicles in Transport Canada database. Transport Canada defines safety-related defects as those that interfere with the safe functioning of the vehicle and are present in a group of similar vehicles [25]. Such defects are not due to normal wear and tear, operator negligence, nor inadequate maintenance, and may cause problems that occur with little or no warning that endanger the safety of road users. If motor vehicle owners in Canada suspect safety-related defects in their vehicles, they can report them to Transport Canada. Once a defect is reported, the defect complaint is entered into the *"Defect Complaints Database"* and reviewed by an analyst. If warranted, Transport Canada will initiate an investigation into the complaint that may result in recalls.

2.2.3 Rapid Alert System for non-food dangerous products (RAPEX)

RAPEX (*"Rapid Alert System for non-food dangerous products"*) was established in the EU as a rapid alert system that facilitates rapid exchange of information between member states of the EU and the European Commission on measures taken as a result of products posing risk to consumers. RAPEX relies on close cooperation between the Commission and individual national authorities of participating member countries.

RAPEX has notifications going back to the year 2006. In this dataset, each notification record has a risk level. The risk level can be "Serious" or "Other". The risk level is also classified based on the type of user distinguishing consumer or professional users. Each record has the week and year of notification, a reference number, the country that notified, and detailed description of the product including the name, category, type, batch number, and, in many cases, also a picture of the product. The notification also lists the risk type, which is the kind of injury that can result from the hazard, and includes risk types such as burns, electric shock, etc. [20]. Finally, a notification also includes information about the measures taken by the notifying country to mitigate risks from the product.

The notification process for RAPEX starts with the identification of a risk with respect to a product. The identification of risk can happen by a competent national authority, or the manufacturers and distrib-

utors of the product. Manufacturers and distributors must inform the national authority of any dangerous product, specifically consumer products that are on the market and present a risk to consumers (like electric shock, injury, etc.) such that the product may not remain on the market [26]. In this case, manufacturers and distributors should take appropriate preventative and corrective actions. When this identification happens, either the appropriate authority or the responsible business takes relevant measures to eliminate the risk. These measure can include withdrawing the product from the market, recalling the product from consumers, or issuing warnings. As a next step, each RAPEX national contact point informs European Commission about the product and all relevant information. The European Commission then disseminates this information to all participating countries [26].

2.2.4 Differences between Datasets

Though the primary purpose of the data in these three datasets described above is to inform the consumer of issues that may be affecting a particular model of a vehicle, there are differences in the amount and format of data available in each dataset. The NHTSA and Transport Canada notifications do not contain columns to indicate the risk level of the problem. On the other hand, RAPEX notifications indicate risk level by classifying the notifications as serious or other. The NHTSA and Transport Canada datasets do not classify the risk into a fixed type of risk, and instead, their notifications describe the consequences of the defect. RAPEX classifies notifications based on a fixed number of risk types like asphyxiation, burns, chemical, fire, injuries etc. Another difference is that the NHTSA and Transport Canada datasets do not identify the country of origin of motor vehicle. However, RAPEX notifications have the country of origin of the vehicle. NHTSA does not regulate vehicles that are primarily intended for off-road use such as all-terrain vehicles (ATVs), snowmobiles, dirt bikes, etc.—which are regulated by the Consumer Product Safety Commission [CPSC])—while the Transport Canada and RAPEX datasets each have notifications about off-road vehicles.

2.3 Classifying E/E Notifications

We analyzed the datasets through two separate means. The first method used a manual classification involving two people and two reviewers and was performed for the Transport Canada, the RAPEX, and partially for the NHTSA dataset. The second method was an automated classification using text-based searches to classify notifications involving E/E systems and was performed for the NHTSA dataset.

A classified E/E notification is a *false positive*, if the actual cause of the corresponding defect was *not* due to problems in the E/E system. For example, if a notification was classified as an E/E notification in the tires that was in no way related to any E/E system (e.g., a tire pressure monitoring system) like improper tire pressure labeling, this would be a false positive. An E/E notification would be a *false negative*, if it was not identified. Any classification can include incorrect assignments, usually reported as *precision* and *recall*. In our case, precision is the fraction of notifications that were labeled as E/E notification and should be E/E notifications. Precision is degraded by false positives, which are notifications labeled as E/E, but that only mention other technologies. Recall, as a quantitative metric, is the fraction of E/E notifications relative to all E/E notifications. Recall targets characterizing false negatives, since recall is affected by classing notifications as Non-E/E although they are E/E notifications. In the ideal case, there are no false positives and no false negatives. There are several reasons this classification is performed for notifications and not for defects. First, the datasets only contain information on notifications that may or may not be correlated with known defects. This may occur in recent model year vehicles for which regulators and manufacturers have not yet initiated notifications, as defects may still be unknown. In the ideal case, this classification would find the set of all E/E defects and not the set of all E/E notifications, but this is impossible as these defects may be unknown. Additionally, the datasets themselves could contain false positives and false negatives, although the regulatory process should minimize these mis-classifications. Another reason for mis-classifications is due to grammatical and spelling errors, which may be detected and corrected easily in manual review, but is difficult to handle for automated classification, but may be handled with sophisticated natural language processing (NLP) techniques.

2.3.1 Manual Classification and Review

We used full manual classification for the Transport Canada and RAPEX datasets, and partial manual classification for the NHTSA dataset. Full manual classification involved two persons categorizing the notifications into the categories of E/E or Non-E/E. For the RAPEX and the Transport Canada datasets, two undergraduate students investigated one notification at a time and assigned an appropriate label to them.

computer	software	firmware	electronic control unit	ecu	engine control module
ecm	re-flash	re-program	control module	control unit	bug
version	update	program	overflow	electronic	electric

Table 3: Keywords used for automatic classification of the NHTSA dataset.

To ensure high precision and high recall, and thereby high quality, we used an independent validation step after the manual classification. After the two undergraduate students completed the classification, one of the co-authors randomly selected a small subset to validate the classification. Any found mis-classification was subsequently corrected. On top of the validation, we also performed automated sanity checks to inspect specific notifications. For example, we carefully reinspected all notifications that carried the system type "Electrical" in the Transport Canada dataset, and double-checked all notifications that contained specific keywords, such as, for instance, motor, ECU, short circuit, and software. For the NHTSA dataset, one of the co-authors manually inspected the entries that we identified using a search-based classification. The purpose for this inspection was to identify and eliminate false positives to improve precision. In particular, it also highlighted certain bad keywords that resulted in high rates of false positives, such as "upgrade," that were excluded from subsequent keyword searches.

2.3.2 Automated Classification

Automated classification was used for the NHTSA dataset, followed by the manual review discussed in Section 2.3.1. The NHTSA dataset contains several fields that have natural language data (i.e., English sentences and text), such as the "Defect Summary" (`DESC_DEFECT`) field. Specifically, each notification includes "Defect Description," "Defect Consequence," "Corrective Action," and "Notes" fields contain natural language descriptions of the defect, its correction, etc. that are used in classifying the notification as an E/E notification. Additionally, the "Component Name" field contains a semi-categorical name of the defective component (system) and was also used for classification. The "Component Name" field includes, for example, categories such as "ELECTRICAL SYSTEM: SOFTWARE". However, we did not classify by solely the "Component Name" field because many E/E notifications are not precisely categorized. For instance, some notifications for software defects, such as NHTSA notification 04V254000, are not correctly categorized as "ELECTRICAL SYSTEM: SOFTWARE," along with several others shown in Table 4. Each of these fields were searched using regular expressions for the set of keywords in Table 3.

Spacing was required between short keywords (e.g., for "ecu") and all standard permutations of keywords were used (e.g., "re-flash," "reflash," "re flash," etc.). If any substring in these fields matched any of these keywords (case insensitive and allowing permutations for spacing), they were classified as candidate E/E notifications that were then manually reviewed. Additionally, the NHTSA dataset contains many effectively duplicate entries that were accounted for (when necessary) by using the campaign number to uniquely identify the notifications to not duplicate counts of the number of affected vehicles or numbers of notifications.

3 RESULTS FROM ANALYSIS OF THE DATASETS

With access to these datasets, we could investigate a number of questions for E/E notifications. This section describes four questions we looked at in detail. Additional observations are part of Section 5.1.

3.1 E/E Systems are Increasingly Becoming a Problem

The dataset analysis indicates that E/E notifications have been increasing in recent model year vehicles and for notices issued in recent years. Specifically, E/E notifications are increasing over time in the Transport Canada and the NHTSA datasets in terms of all of the following: (a) the percentage of E/E notifications compared to Non-E/E notifications per model year (Figure 1), (b) the absolute numbers of vehicles and systems affected by E/E notifications compared to those affected by Non-E/E per notification year (Figure 2), and (c) the absolute number of notifications per vehicle model year (Figure 3). The RAPEX dataset also confirms this when looking at the total number of notifications over the years (Figure 6).

3.2 E/E Notifications have Greater Delay than Non-E/E Notifications

An interesting question is to determine whether certain types of notifications reach further back in time than others. We interpret this as being that the particular defect identified in the notification has taken longer to be detected than notifications that reach back fewer years.

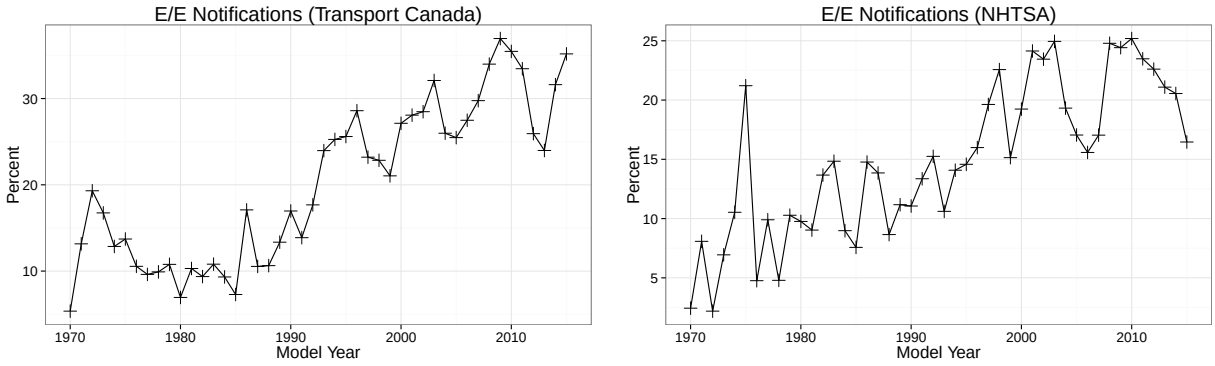

Figure 1: Transport Canada and NHTSA percentage of E/E notification out of all notifications across all makes and models versus model year.

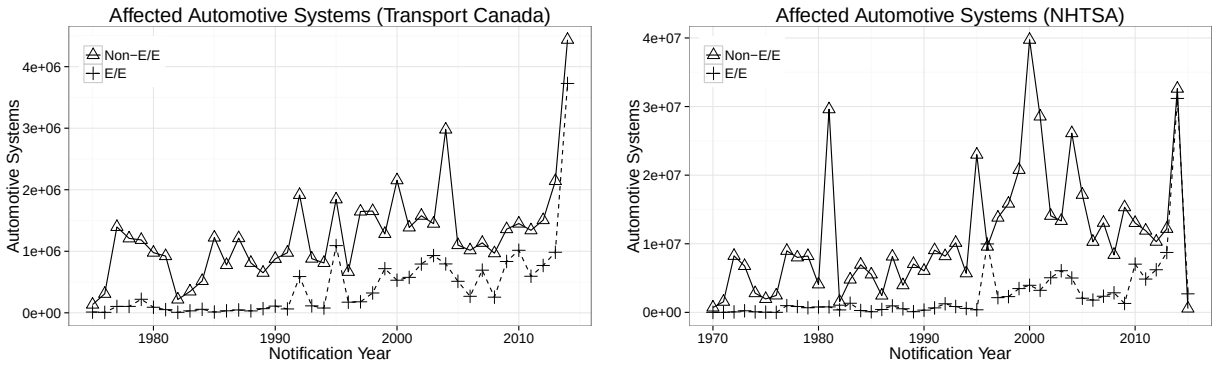

Figure 2: Transport Canada and NHTSA sum of the number of vehicles potentially affected by notifications versus notification year, categorized into E/E and Non-E/E notifications.

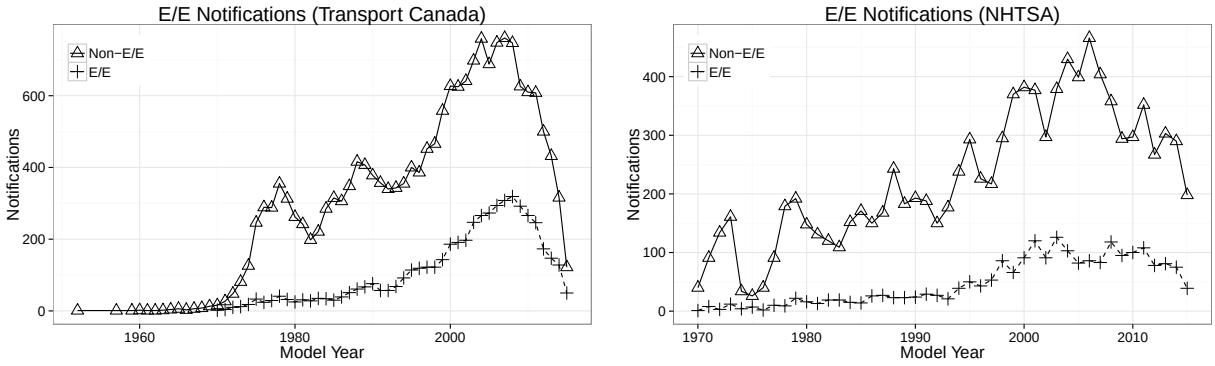

Figure 3: Transport Canada and NHTSA E/E and Non-E/E notification counts versus model year.

The delay of a notification is the date of the notification minus the starting manufacturing date. Figure 4 shows notification delays, categorized into E/E and Non-E/E notifications. In the Transport Canada dataset, the dates of manufacturing are not available, so the notification delay is approximated as the year of the notification minus the model year. If multiple models and model year vehicles are effected, the date or earliest model year across all the affected models will be used. For example, if a notification covered three models over different model years (2005 to 2010, 2007 to 2010, and 2005 to 2008), then the approximated delay will be $2011 - 2005 = 6$ years. While ideally the manufacturing date would be used instead of the

model year date, the manufacturing date is not always available in the datasets, while the notification date, affected models, and model year are more readily available.

Both datasets show that on average, E/E notifications reach back further than Non-E/E notifications. Thus, recent model year vehicles may also be correlated with having additional E/E defects that have not yet initiated notifications. In the Transport Canada dataset, the notification delay mean was 2.21 years for E/E defects and 1.83 years for Non-E/E. In the NHTSA dataset, the notification delay mean was 2.23 years for E/E defects and 2.14 years for Non-E/E. The differences between the notification delay was statistically significant (Wilcoxon rank sum test) for both datasets. These results are highlighted by E/E notifications such as NHTSA recalls 11V395000 and 14V047000 described in Table 4, that each had delays of around six years.

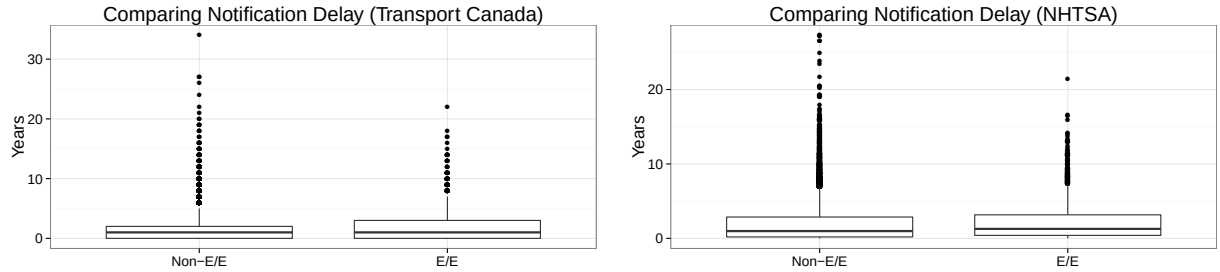

Figure 4: Transport Canada and NHTSA notification delay between E/E and Non-E/E notifications from 1970 to 2014 model years are illustrated as box plots.

3.3 E/E Notifications Appear for Electrical Components, Lights, and Airbags Most Frequently

The dataset from Transport Canada and the NHTSA categorized the notifications based on the vehicle subsystem that was affected. Transport Canada splits the data into 20 categories. The NHTSA uses 26 categories with additional sub-categories. The interesting question is which subsystems are prevalent in E/E notifications. Based on the datasets, we can identify the subsystems that are most likely affected by E/E problems within each jurisdiction. Figure 5 shows the frequency to which subsystem category the notification was assigned to in the different datasets.

A direct comparison is impossible, because the different datasets split up the notifications into different categories, and also the dataset from Transport Canada has generic category called *"Electrical"* that dominates the notifications related to E/E systems. Furthermore, due to regional influences, the datasets contain different data (see Section 2 for these differences). Nevertheless we can still provide a subjective, qualitative

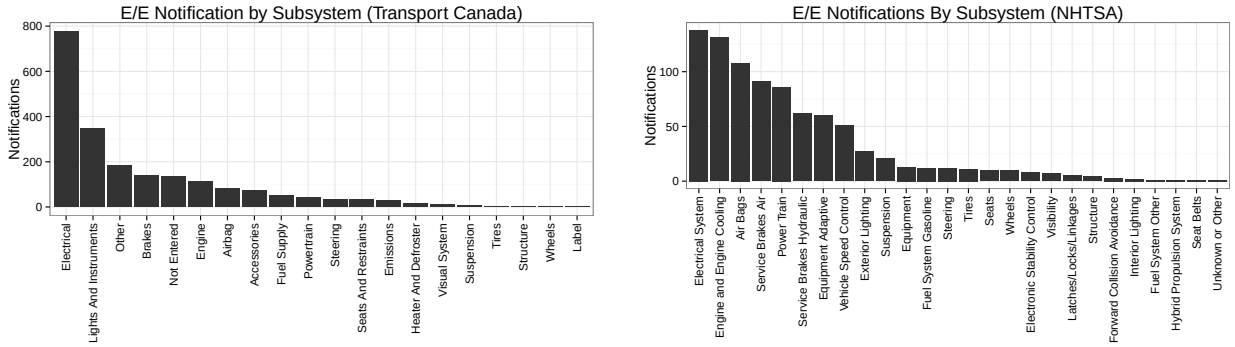

Figure 5: Subsystems specified for notifications related to E/E problems.

interpretation of the data in Figure 5. Subsystems that seem to rank highly when comparing notifications related to E/E problems are (in no particular order): air bags, lights and instruments, engines, brakes, and

the power train. For this categorization, we combined: brakes (i.e., "Service Brakes Hydraulic", "Service Brakes Air" in the NHTSA and "Brakes" in the Transport Canada dataset), power train (i.e., "Throttle Control", "Power train", "Transmission Control"), and instruments (i.e., "Lights and Instruments", "Lights", and "Instrument Cluster").

3.4 E/E Notifications Dominate Others with Respect to Fire Hazards

RAPEX provides detailed information on the risk types for the components involved in the notification. The dataset uses four distinct categories for the types of risk: burns, fire, injuries, and chemical. Some notifications list a combination of risk. For example, RAPEX notification 0615/11 lists a hazard involving a potential fuel leak and the ECU causing a fire by means of a short circuit. The notification therefore has the risk labels "Fire|Injuries". In our analysis, we will count this notification twice: once for the risk type being "Fire" and once for the risk type being "Injuries".

The RAPEX dataset distinguishes between the fire and burn hazards. The risk of a burn is one where a participant can get inured, but the failing component will not start a fire. As an example, two notifications that have the risk type "Burns," but not "Fire," are motorbike exhaust pipes that may lose their enclosure or seat heating elements that are overheating and charring the seat. Specific notifications in the RAPEX dataset are A12/1541/12, 0007/10, and 0767/11.

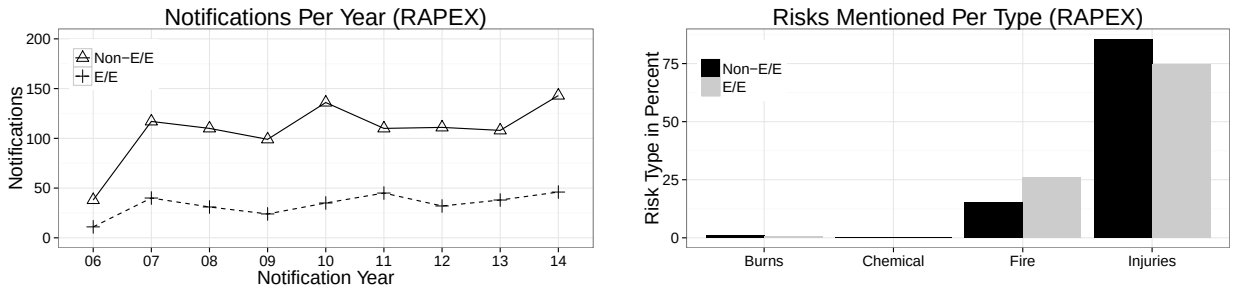

Figure 6: E/E and Non-E/E notifications in the RAPEX database (left). Comparison of the risk types for E/E vs. other components. Note: some notifications mention several risk types, so the total is not 1 (right).

Analyzing the RAPEX dataset, we discovered that E/E notifications dominate the risk type "Fire". Figure 6 shows a breakdown of the percentages for each risk type. About 25 percent of all notifications related to E/E systems specify a fire hazard, while only 15 percent of other notifications carry the risk type "Fire". Conversely, fewer E/E notifications are tagged with the risk type "Injury".

4 SPECIFIC E/E NOTIFICATIONS

This section describes specific E/E notifications identified in our analysis. Summaries of several specific E/E notifications appear in Table 4. As illustrated by Table 4, E/E notifications have involved nearly all types of motor vehicles, including buses, ambulances, motorcycles, passenger vehicles, passenger trucks, and cargo trucks. Additionally, E/E notifications have involved a diversity of energy sources, including gasoline, diesel, all electric, hybrid electric/gasoline, and natural gas. The affected systems involved in E/E notifications include airbags, seatbelt pretensioners, cruise control systems, electronic stability control systems, battery charging controllers, brakes, engine overheating, transmissions, engine and powertrain control, tire pressure monitoring systems, and many others. Additionally, there have been several instances of E/E notifications for unintended acceleration as summarized in Table 5. Of particular interest currently are notifications that involve computers and software. The root problems are also diverse, albeit somewhat difficult to ascertain from the data available, but certainly include wrong values specified in software (including calibration values), timing errors, wrong values computed by software, sign errors, among others. The earliest notification mentioning "computer" was in 1975 for 75V117000, the earliest notification mentioning "software" was in 1996 for 96V007000, and the earliest notification mentioning "over-the-air software update" was in 2014 for 14V006000. Additionally, while specific makes and models were explicitly not listed to avoid singling out particularly makers, models of all makes have been the subject of E/E notifications. Other authors have compiled interesting motor vehicle E/E issues previously [27].

Camp. No.	Date	Pot. Aff.	Type	Model Years	Problem	Resolution
75V117000	JUN 23, 1975	8 500	Cargo truck	1971-1975	Brake loss due to anti-lock computer malfunction	Replace computer
85V134000	OCT 22, 1985	3 988	Passenger car	1985	ECU timing problem	Replace ECU
96V007000	JAN 16, 1996	10 600	Passenger car	1996	Climate control module software failure	Replace module
00V374000	NOV 13, 2000	492	Electric passenger truck	1998	Battery pack overheating	Battery pack module software update
01V025000	FEB 03, 2001	353	Passenger car	1999	Brake warning light does not display due to software problem	Update software in instrument cluster
99E023000	JUL 29, 1999	1 362	Engine	1999	Engine stall because of software	Update ECU software
00V131003	MAY 30, 2000	3	Cargo truck	2000	Wrong gear selection in transmission due to software problem	Replace autoshift transmissions
13V040000	FEB 06, 2013	3 644	Passenger car	2003-2004	Unintended airbag deployment	Replace controller
04V254000	MAY 27, 2004	8 189	Motorcycle	2004	Wrong speedometer reading	Software update
05V208000	APR 27, 2005	153	Natural gas bus	2002-2005	Unexpected throttle surge due to compressed natural gas ECU	Update ECU software
05V153000	APR 15, 2005	216	Ambulance	2002-2005	Electric power sequencing problem causing overheating and fire risk	Install new transistor board
11V395000	AUG 04, 2011	1 512 107	Passenger car	2005-2010	Stalls due to transmission damage	Update automatic transmission control module software
14V047000	FEB 10, 2014	2 190 934	Passenger car	2005-2011	Engine and airbag disabling due to ignition switch disconnection	Replace ignition switch
06V220000	JUN 19, 2006	433	Passenger car	2006	Certain operating conditions lead to engine compartment temperature increase that may damage alternator	Improve engine compartment cooling, modify ECU, and install new alternator
06V493000	DEC 29, 2006	50 665	Passenger car	2007-2008	Brake lockup	Reprogram the ABS ECU
13V500000	NOV 01, 2013	344 187	Passenger car	2007-2008	Unintended braking by Vehicle Safety Assist System (VSA)	Instal new yaw rate sensor
08V595000	NOV 14, 2008	2 500	Passenger car	2008	Transmission software may perform a multistage downshift that could stall the car	Reprogram engine and transmission control unit software
11V534000	NOV 04, 2011	38 444	Passenger car	2008-2009	Delay of 30ms between first and second dual-stage airbag deployment resulting in head injury criteria requirements non-compliance	Reprogram sensing and diagnostic module
12V064000	FEB 17, 2012	20 512	Motorcycle	2008-2011	Insufficient battery charging leading to stalls	Replace voltage regulator
13V233000	JUN 04, 2013	254 396	Passenger car	2010-2012	Seatbelt pretensioner and airbag non-deployment in crash	Software update
14V053000	FEB 12, 2014	698 457	Hybrid passenger car	2010-2014	Stalls due to power electronics shorting	Software update for motor/-generator control ECU and hybrid control ECU
14V522000	SEP 02, 2014	1 810	Electric car	2010-2014	Brake vacuum pump malfunction	Reprogram or replace brake vacuum pump controller
13V283000	JUL 02, 2013	224 264	Passenger car	2013	Wrong side airbag deployment	Flash occupant restraint control module
13V328000	JUL 29, 2013	11 097	Motorcycle	2013	Stall under deceleration	Replace ECU
14V006000	JAN 13, 2014	29 222	Electric car	2013	Overheating power cables while charging	Over-the-air software update
14V138000	MAR 25, 2014	989 701	Passenger car	2013	Occupant classification system (OCS) may classify seat as empty when occupied	Update OCS software
13V506000	OCT 17, 2013	207	Passenger car	2013-2014	Remaining fuel overestimation leading to possible stalls	Update instrument cluster software
14V173000	APR 03, 2014	5 700	Passenger car	2014-2015	Power Control Module (PCM) stops charging battery	Reprogram PCM
14V551000	SEP 10, 2014	19	Diesel cargo truck	2015	Engine stalls due to incorrect parameter setting in software	Reprogram ECU

Table 4: Specific E/E notifications from the NHTSA dataset, where *"Camp. No."* is the NHTSA campaign number, *"Date"* is the notification date, and *"Pot. Aff."* is the number of potentially affected units.

Camp. No.	Date	Pot. Aff.	Type	Model Years	Resolution
03V033000	FEB 05, 2003	19 500	Passenger truck	2003	Reprogram ECU
10V231000	JUN 01, 2010	372	Low speed vehicle	2010	Accelerator pedal replacement
13E068000	DEC 12, 2013	496	Transmission	2010-2013	Update hybrid control module software
13V633000	DEC 16, 2013	29	Bus	2013	Update hybrid transmission software
14V026000	JAN 30, 2014	22	Bus	2014	Update hybrid transmission software
14V042000	FEB 07, 2014	114	Bus	2014	Update hybrid control module software
14V303000	MAY 28, 2014	2	Bus	2014	Update hybrid control module software
14V583000	SEP 22, 2014	6 562	Passenger car	2015	Reprogram engine control module (ECM)

Table 5: E/E notifications for unintended acceleration, where *"Camp. No."* is the NHTSA campaign number, *"Date"* is the notification date, and *"Pot. Aff."* is the number of potentially affected units.

5 DISCUSSION AND LIMITATIONS

During the analysis of the different datasets, we made several observations that are relevant to put the work into context and should be interesting for work that repeats our analysis with future data.

5.1 Observations

The datasets show a clear upward trend in the number of E/E notifications. This trend has an obvious correlation with the number of ECUs reported for motor vehicles (Table 1). Our conjecture is that since recent motor vehicles have significantly more and more complex E/E systems (e.g., computerized control of all subsystems is standard and active driver assistance systems are becoming available), this inherently leads to more problems related to E/E systems. Consequently, the absolute number of E/E notifications increases over the years. Additionally, it is common to reuse E/E systems across vehicles, so the number of vehicles potentially affected by an E/E notification is also typically higher than for Non-E/E notifications.

Not all countries make their datasets accessible. We tried to obtain datasets from many different sources, however, the quality of the data available and the access methods vary. For example, the NHTSA and Transport Canada make the complete dataset available for download in one database file. The UK also provides a dataset that may be downloaded as one file, but that we did not analyze in this study [28]. RAPEX only provides an online interface that permits exports of at most 1000 entries at a time. The Kraftfahrt-Bundesamt (German) provides no download option and intentionally limits (as confirmed with the Kraftfahrt-Bundesamt) searching for notifications to only specific entries after entering brand, model, year, and type of notification (e.g., brakes). Australia provides static web pages with very limited ability to search [29]. Furthermore, the Australian site only lists rudimentary information about each notification. We contacted the Australian organization (the Australian Competition and Consumer Commission [ACCC]) to acquire the dataset, but at the time of this writing, we have not received a response. The inaccessibility of datasets limits the ability to perform an analysis of notifications on a global scale. We hope that in the future, more governments will embrace an open data mentality, and make the data easily accessible. Additionally, we hope that the regulatory authorities will make permanent URLs available for all notifications (e.g., using the campaign numbers), as the URLs we give in Table 4 and 5 may break over time.

Some datasets do not use a controlled vocabulary to ensure consistent labeling. Libraries use a controlled vocabulary, usually called thesaurus, to ensure that entries in the dataset are labeled consistently. The NHTSA and Transport Canada seem to use a controlled vocabulary, because we did not find many inconsistencies between entries. RAPEX does not seem to use a controlled vocabulary. Consequently, notifications concerning vehicle safety can be filed under, for instance, "passenger vehicle" or "passenger car". Furthermore, the lack of a controlled vocabulary permits spelling mistakes and makes certain notifications difficult to find. For example, we found one entry that misspelled the word "vehicle" and was consequently not found with the original search terms. Finally, the RAPEX database seems to contain a number of spelling mistakes across different columns in the notifications, as well as inconsistent style. For example, in the column on measures adopted by the notifying country, some entries have a colon symbol at the end (e.g., "Voluntary measures: Voluntary corrective action taken by the manufacturer:"); or just a typo as in "Voluntary measures: Voluntary corrective actions take by the importer". We have informed the maintainer of the dataset of these inconsistencies, but at the time of the submission have not heard whether they will address them.

The datasets provide different content and consequently a direct comparison to evaluate bias becomes impossible. Each dataset contains data that is not contained in the other datasets. For example, the RAPEX dataset contains a significant number of notifications for motorcycles, while the dataset from Transport Canada includes recreational vehicles, all-terrain vehicles (ATVs), and snowmobiles. Finally, the NHTSA dataset includes detailed supplemental information (e.g., how to fix the problem and the response from the manufacturer and access to significant supplementary documentation), while the other datasets only include short text fields. The significant differences between the type of data stored in the datasets unfortunately prevented us from more sophisticated comparisons. It would have been interesting to relate the data and identify potential bias of the different agencies involved in processing and publishing the notifications.

5.2 Threats to Validity

We actively tried to reduce classification errors in our manual classification. The classification completed by the two undergraduate students was reviewed by one of the co-authors of the paper. The review consisted of two phases. The first phase involved automated sanity checks on the data. For example, do all notifications with the same notification ID, but assigned to different vehicle models, have the same overall classification. In other words, we checked whether a notification has inconsistent labeling. Any elements found during the sanity checking were returned to the undergraduate students for re-classification. The second phase involved a review of a subset of the classified notifications to confirm that they are correctly labeled. Nonetheless, mis-classifications can still happen and judging whether a notification is an E/E notification based on a short textual description is subjective in several cases. Additionally, all analysis presented included all entries in the datasets, which may also cover systems like tires, child seats, etc., so many E/E results presented may be conservative estimates since tires and child seats are generally Non-E/E, although the total numbers of these notifications represent at most a few percent of the notifications.

An additional criticism of the analysis presented in this paper is that it could be subject to confirmation bias. As an attempt to avoid confirmation bias, we used multiple independent datasets, and the Transport Canada and RAPEX datasets were analyzed independently from the NHTSA dataset. The datasets were also compared for consistency to publicly available aggregate reports, such as the 2012 NHTSA Annual Report [30]. For the aggregate analyses presented in the figures in this paper, the Transport Canada and RAPEX datasets were analyzed using R and the NHTSA dataset was analyzed using MATLAB. All figures in this paper were created using R. Additionally, we do not make any claims that increasing numbers of E/E systems in motor vehicles is correlated with or decreases overall safety, such as measured using numbers of fatalities, injuries, or crashes.

Since the datasets can contain spelling mistakes, our data might be incomplete. For example, for the RAPEX dataset, we used specific search terms to extract notifications for motor vehicles. Spelling mistakes in the original dataset (e.g., "vehilce" instead of "vehicle") are not picked up by the search terms and consequently excluded from the list. Also in the automated classification performed on the NHTSA dataset, spelling mistakes will have significant consequences. We tried to counteract this by searching for slightly misspelled versions of the text, however, naturally, we might have missed something. A better solution would be to use natural language processing (NLP) tools, which we plan to do in the future. We still believe that our dataset is comprehensive and representative, because in the occasions where we found misspelled words, the search produced only a single or a few matching records.

5.3 Takeaway Messages: A Call to Action

Next, we discuss several takeaway messages from this survey of E/E notifications for motor vehicles.

Fixing things late is expensive. This discussion would be remiss without mentioning the recent Toyota unintended acceleration problems, which did not have E/E notifications in the datasets analyzed. Sudden unintended acceleration is the unintended, unexpected, uncontrolled acceleration of a motor vehicle [31]. As is well-known in software and systems engineering, correcting problems late in the development process, or after deployment, can be expensive (financially, in manpower, delays to market, reputation, etc.) [32, 33]. These unintended acceleration investigations highlight this observation, albeit in an extraordinary way beyond the typical finding a defect late in the development cycle and having to redesign and retest to fix it. This scenario did have two related Non-E/E notifications, together affecting over 4.5 million vehicles with model years from 2004 to 2010 of several models, for pedal sticking and floor mats (09V388000 and 07E082000). NASA and the NHTSA conducted a ten month study of the Electronic Throttle Control System (ETCS) and failed to find any definitive electronic or software causes for the unintended acceleration [34, 35, 36]. The

investigations concluded that the unintended accelerations were likely due to three possible reasons: operator misapplication, accelerator pedals sticking, or accelerator pedal entrapment in the floor mat. However, the 2013 Bookout v. Toyota case was premised partly on there being problems in the ECTS architecture and software [37]. During the testimony in this case, problems in the ETCS architecture and real-time software were explored, and a conclusion was drawn that some best practices were not followed that made the ETCS be another possible source of unintended acceleration [38, 39, 40].

In 2014, the US Department of Justice (DOJ) made a USD $1.2 billion criminal penalty charge as a part of the unintended acceleration problems [40, 41]. The NHTSA also levied the maximum fines, for a total cost of $48.8 million [42]. Additionally, in 2013, related class action lawsuits were settled for a total cost of USD $1.6 billion [40, 43]. Publicly available reports [34, 36] and additional details that arose in the Bookout v. Toyota case [38, 39, 40] suggest that the software codebase covered in the ETCS was on the order of 1 million source lines of code (LOC) [44, Table A.7-1]. Combining solely these three large legal costs to a total of approximately USD $2.85 billion suggests a per-LOC cost of between $285 to $2 850. This estimate of the per-LOC cost excludes other real costs such as those from development, testing, etc., but of course also excludes both (a) liability of the other possible sources of unintended acceleration (user error, pedal sticking, and floor mat entrapment), and (b) the cost of other (non-software related) aspects of the engineering, manufacturing, and other processes. Typical estimates of software development cost per-LOC range from around USD $10 in general embedded systems to USD $50 in aerospace and medical devices [45]. From this purely financial standpoint, perhaps additional investment in the earlier development, engineering, and verification and validation stages are warranted in motor vehicle engineering, particularly with regard to E/E systems and software, especially with the move toward autonomy and connected vehicles that will rely on more complex E/E systems.

Need for better validation and verification methods. With the surge of active driver assistance systems (ADAS), the number and complexity of E/E systems in cars will increase drastically. Consequently, the validation and verification methods used for E/E systems must scale with this surge. Furthermore, the integration of these new ADAS will require additional attention as the testing effort will grow exponentially with the increased number of E/E systems. Finally, the current methods will need to be adapted to cope with new challenges such as sensor fusion [46] and machine learning for ADAS.

Improved collaboration between international data sources. The datasets provided by the different regulatory agencies (the data sources) are not directly comparable. Additionally, while the NHTSA maintains information on foreign notifications (http://www-odi.nhtsa.dot.gov/frecalls/), this does not include the same information and is not in the same format as the US domestic notification information. The regulatory burden could perhaps be more easily spread across nations, or at least the information collected should be consistent.

Security problems are ignored at the moment. An interesting aspect is that the notification datasets lack information on security risks (other than some instances for vehicle entry and theft). Security is a serious threat to modern vehicles and can affect safety [47, 48, 11]. As vehicles become increasingly connected (such as through communications like vehicle-to-vehicle and vehicle-to-infrastructure [49]), security will play an increasing role in generating E/E notifications. It is not clear if including security notifications in the (primarily safety-related) datasets analyzed in this study is the right action plan. Creation of a motor vehicle security notification dataset and reporting service—similar to those operated by various companies and the US government through the US Computer Emergency Readiness Team, https://www.us-cert.gov/—may be the right path forward for tracking and reporting security defects in vehicles. Regardless, regulation of security in vehicles is likely to occur in the coming years (as indicated by recent legislative reports [50] and ongoing lawsuits [51]), and regulatory agencies should monitor security defects in motor vehicles and maintain notifications for them.

6 CONCLUSION

This paper used datasets on safety-related notifications for motor vehicles from three different jurisdictions (the United States, Canada, and Europe) to identify facts and trends related to E/E systems. We have identified the trend that E/E-related problems are increasing over time, shown evidence that E/E defects are latent for a longer time than Non-E/E defects, identified that E/E systems are more prone than Non-E/E systems to fire hazards when defective, and finally provided a ranking of the systems related to E/E notifications. Based on this analysis, a couple additional observations, and the compelling concrete examples, we formulated a call to action for researchers, regulators, and manufacturers. The analysis presented in this

paper is only the first step. In future work, we plan to further refine the labeling in the database, for example using NLP [52], and build prediction models based on the data.

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DISCLOSURE STATEMENT FOR CONFLICTS OF INTEREST

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