EVALUATION OF IMPACTS OF IT-INCIDENTS ON AUTOMOTIVE SAFETY WITH REGARD TO SUPPORTING REACTION STRATEGIES FOR THE DRIVER

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Paper Number 15-0156

ABSTRACT

Objectives

The integration of modern IT technologies into vehicles brings up several new challenges in automotive systems engineering. While current technology aspires an exclusive use of electrical and electronic control systems for relevant functions, such as engine control or X-by-wire systems, growing dependency on electronic systems increases the vulnerability of modern cars to both accidental and intentionally forged IT incidents. Especially the constantly increasing complexity of and interdependencies between different automotive IT systems makes it difficult for the developers to foresee all potential fault conditions or to prevent unauthorized actions from taking effect. As if these problems were not enough of a challenge, especially in automotive IT environments IT- incidents can possibly also affect the safety of the car, its passengers and other road users.
Building on a study on IT security warnings [1] and comparing with corresponding ASIL levels, we carried out a driving simulator study to evaluate driver reactions to various error and security relevant scenarios.

Methods

Assuming that malfunctions of electronically supported control systems will endanger the safety of the car, a driving simulator study was designed and executed. These tests cover both security-related and safety-related lsources of failures (i.e.: accidental or provoked malfunctions) and scenarios with different criticality (based on ASIL A, B, C, D – [2]). The reactions of 40 uninformed drivers were observed and analyzed. In particular failures of engine, steering and brakes were executed in different road and traffic scenarios (e.g.: slow vs. high speed, low vs. high traffic density). The reactions of the drivers were recorded and, additionally, the controllability of the situation was observed as perceived by the drivers (using a think-aloud test). Furthermore, the study evaluated the potential of appropriate warning and reaction strategies that could support the reaction of the driver in critical situations as developed in [1].

Results

The results show differences in driver behavior within a specific failure situation and an even greater degree between various failure situations. We found different types of accidents following the loss of steering and braking function – but no accidents caused by the loss of engine function. Interestingly, the results show the highest rate of recognition for the engine turn off scenario, where as in the autonomous acceleration and loss of brake function 15-17% of drivers did not recognize the malfunction. Besides this, we introduce different strategies to warn and support drivers in such situations. Especially when losing the ability to steer and brake, the warnings showed positive impact if the driver is warned ahead and stops the car before the complete loss of those functions. When the warning appears together with the function loss, a significant improvement of crash count and severity could not be observed.

Conclusions

This work shows the impact security-related incidents can have on the safety of concurrent and future vehicles. It shows the potential of decreasing the severity of these incidents by using tailored warnings and shows a first evaluation of the feasibility of such an approach. It was shown that a loss of engine function leads to a safe stop of the car while a loss of steering or braking ability or an autonomous acceleration lead to an accident in 45% up to 71% of all cases. The severity of those accidents is not significantly correlated to the type of malfunction.

INTRODUCTION

Concurrent automotive systems are more than mere mechanical systems. With a broad array of embedded systems, a modern car is akin to a driving computer network. This network consists of various electronic control units (ECU) which communicate using different bus-systems (see [3] for further details). These ECUs implement various functions. Simple ECUs control simple components like the window openers while more complex ECUs handle more complex tasks like engine control. Other embedded systems support the driver by giving him information about the environment or suggesting a route. All these factors establish cars as complex multimedia systems (as discussed in [4] On one hand this opens a broad range of possibilities to interact with and support the driver. On the other hand all these interconnected electronic components enlarge the error-proneness and attack surface of the automotive system. Looking at the security aspect, in automotive scenarios there is always the risk that unauthorized tampering with car IT can escalate into a safety incident – with the risk of the driver losing control of his car. Based on prior work from us where we demonstrated real IT attacks on several automotive subsystems ([5], [6]), such common automotive vulnerabilities have also been illustrated later on full cars by [7] and [8]. The spectrum of observed results leads up influencing the brakes, the steering wheel or disabling the engine by specially crafted CAN bus commands. As these practical analyses have substantiated, unforeseen IT incidents (like intentional, IT-based attacks) also bear severe safety implications. This contribution therefore focuses on the impact of (e.g. security-related) IT incidents on the safety of automotive systems. However, also unintended malfunctions (e.g. caused by system/component defects, software coding errors, or unforeseen and unhandled system interdependencies) could cause similar results. With reference to different examples of such potential incident causes, the aim of this paper is to analyze reactions of drivers in different incident scenarios with different grades of safety criticality.

A Model to Describe Safety and Security Relevant Consequences

As a first step we revert to the Automotive Safety Integrity Level (ASIL), a model to describe consequences of safety and security-related incidents. This model allows us to specify various safety-related incidents and to evaluate their severity with regard to automotive scenarios. ASIL is defined in ISO 26262 ([2]) and consists of three components:

- Severity (S) is the severity of potential harm caused by an incident (similar to the SIL). It ranges from S0 (no injuries) via S1 (light and moderate injuries) and S2 (severe and life-threatening injuries with probable survival) to S3 (life-threatening with uncertain survival or fatal injuries)
- Probability (E) shows how probable it is that such an incident occurs. The levels range from E0 (incredible) via E1 (very low probability), E2 (low probability), E3 (medium probability) to E4 (high probability)
- Controllability (C) evaluates if the driver would be able to control the situation if such an incident occurs. It ranges from C0 (controllable in general) via C1 (simply controllable) and C2 (normally controllable) to C3 (difficult to control or uncontrollable)

These three categories allow a categorization of various incidents in respect of their severity. As a further concept ASIL contains an overall integrity level based on these three components. Similar to SIL, four different levels of differing severity (ASIL A, B, C and D) exist with an additional level for no or very low severity (QM – Quality managementt). Table 1 gives an overview on the impact of the three categories on the overall safety integrity level.

Table1.

Overview on the impact on the overall safety integrity level with highlighted cells representing the tested scenarios

		C1	C2	C3
S1	**E1**	QM	QM	QM
	E2	QM	QM	QM
	E3	QM	QM	A
	E4	QM	A	B
S2	**E1**	QM	QM	QM
	E2	QM	QM	A
	E3	QM	A	B
	E4	A	B	C
S3	**E1**	QM	QM	A
	E2	QM	A	B
	E3	A	B	C
	E4	B	C	D

Using ASIL we are able to evaluate different scenarios in respect of their severity. This allows us to create different test scenarios with varying severity either in respect to their overall ASIL or its components.

Factors in an Automotive Environment

In an automotive environment various factors contribute to othe ASIL. We identify three basic groups of factors which can influence the severity of an incident. These groups deal with the vehicle, the traffic condition and the driver himself. It is important to evaluate all these factors to determine a reliable ASIL for the current situation. As an exhaustive list of factors would exceed the scope of this paper we give a few examples for the various groups of factors.

- Vehicle-dependent factors: This group consists of factors which are inherent to the vehicle and generally don't change rapidly. They consist, for example of:
    - Vehicle type (e.g sports car, bus, transporter, truck)
    - Implemented driver assistance systems (e.g. adaptive cruise control with inherent autonomous acceleration and brake functionality or lane keeping assistant with inherent autonomous steering functionality)
- Traffic-dependent factors: These factors describe the current situation of the traffic or the road. They can change rapidly. Examples consist of:
    - Speed of the vehicle
    - Current lane conditions (e.g. clean or dirty street, potholes)
    - Traffic density (e.g. rural road with no other traffic participants or inner city during work traffic)
    - Weather conditions (e.g. sunny and warm or cold and rainy)
    - Noise (e.g. no outside noises or a lane directly next to a noisy construction site)
- Driver-dependent factors:
    - Response time of the driver for the perception of a certain situation
    - Response time of the driver for the execution of a reaction on a certain situation
    - Quality of the reaction of the driver
    - Interpretation of occurred errors or situations by the driver
    - Physical condition of the driver (e.g. fit or drowsy)
    - Distractions that could influence the attentiveness of the driver (e.g. a nearby airport with a starting plane nearby)

METHODS

We decided to simulate various scenarios of differing severity to record and evaluate the reactions of various drivers. Since the failure of electronic computing control functions endangers the safety of the car, its driver and other traffic participants, we decided to perform these tests using a driving simulator. We created the scenarios according to the formerly discussed ASIL.

The Driving Simulator

We used a driving simulator situated in our lab as the hardware for the tests. It consists of electronic control units (ECUs) and the dashboard of a VW Passat B6 with the ability to trigger instruments such as the tachometer. Furthermore, a forceable and force-feedback steering wheel from Logitech with additional accelerator and brake pedal is integrated into the driving simulator. During the simulation, the driving lane is displayed in front of the vehicle on a semi-transparent screen via rear video projection. We used commercial driving simulation software ([9]) for the simulation of the various test tracks. It provides the adjustment of several factors such as traffic density or the type of vehicle, which will be regarded during the evaluation. Furthermore it offers the possibility to create tracks and specify scenarios.
In order to achieve proper evaluation results 46 test persons were invited to take part in the tests. Thereby each test person has performed four test runs including different scenarios. In the different scenarios the failure of various vehicle components was simulated. As result of the evaluation the reactions of all test persons on these situations were observed, as well as the influence of acoustic and visual warnings on the reaction of the test persons. It should be noted that each test person was only warned in one of the four test runs to prevent the drivers of special expectations during the test runs. Furthermore the appearance of the warning was varied for different test persons, as well as the order of the four chosen scenarios. This was done for the prevention of coherent results and succession effects, which could occur if some combinations of scenario orders with the same appearance of warnings are used to often and could therefore distort the overall evaluation. In total one test run took 1 ½ hour including questionnaires.

Scenarios and derived Hypothesis (ASIL Classification)

We based our scenarios on the different ASIL defined in ISO 26262 ([2]). We created a theoretical scenario for each of the four levels.
ASIL A: In this scenario the engine control unit is manipulated in order to allow law enforcement to safely stop the vehicle using remote access. This scenario implies that the law enforcement agents choose a situation in which the forced stop doesn't endanger other traffic participants. Such a situation implies sparse traffic and low speeds. Hence the severity is rated as S1. The manipulation performed by experts implies a high probability of E4 (e.g. by the means of electromagnetic pulses as researched in [10]. In general the driver will still be able to control the vehicle after the engine is shut down and should be able to stop safely. Therefore, as the derived hypothesis we rate the controllability of this scenario as C2 yielding an ASIL A classification.
ASIL B: In this scenario the car owner tries to manipulate the engine of his car himself, aiming to gain better performance. A failure caused by such manipulation could lead the car to accelerate autonomously while driving, endangering the safety of the driver and other vehicles in the surrounding area. In this scenario we choose an urban area and dense traffic. Hence the rapid acceleration of the car would cause a higher severity of S2. It is not certain that a manipulation of the engine would lead to a malfunction as described. The probability would be rated as E3 though, since most home tuners lack the expertise of professional automotive mechanics. Looking at the high traffic density in this scenario, an affected vehicle would be hard to control. Controllability is rated as C3 in this scenario which leads to an overall ASIL B classification.
ASIL C: This scenario covers another manipulation done by the driver. In this case the driver manipulates his infotainment system to show video (e.g.: TV) while driving. In general this functionality is disabled if the current speed exceeds walking pace. In this scenario, a 3rd party tool to inject forged bus messages with a lower speed signal has been installed by the driver, which would allow him to watch video while driving. As a side effect, this could also set steering support to maximum which could lead to fatal effects especially in high speed scenarios taking place on a speedway (Severity S3) – because these usually require little or no steering support. This causes a relative low controllability for the driver (Controllability C3). As in the previous scenario it is not certain that such a signal manipulation would necessarily propagate to all ECUs. Therefore we rate the probability as E3 again and get an overall ASIL C classification.

ASIL D: In this scenario a potential attacker manipulates the compressor of a heavy transporter. The compressor is also responsible to provide air pressure for the braking process. Such a manipulation would make it impossible for the driver to brake. In this scenario we assume that the transporter reaches the end of a tailback with an option of steering on the hard shoulder and slow down the transporter by engine break function. The momentum of the transporter would ensure fatal consequences which we rated as severity S3 – due to the lack of a higher possible rating. As there would be no control over the brakes any more, the controllability is rated as C3 – again, due to the lack of a higher possible rating. As this manipulation would be performed by an expert, the probability is rated as E4 leading to an overall ASIL D classification.

General Hypothesis

Following the results in the automotive warning research our test drivers should benefit from a warning in general [1]. We expect positive effects especially in ASIL A, B and C scenarios, due to the possibility to brake the car in these scenarios. We used a general warning without any information about the affected system (engine, steering, acceleration pedal or brakes) or reaction strategies (e.g. "Stop car immediately!"). This allows us to investigate the reaction of the drivers as a direct response to the vehicles system failure. Given the timeframe necessary to process incident, deriving, planning and executing an action, we expect a higher amount of false reactions (or no reactions at all) to critical incidents, like the loss of brake or control functionality, due to time constraints. For ASIL A scenario we expect the highest number of correct reactions.

Test Drivers

46 test persons took part in our tests. These persons had an average age of 26.9 years and an average driving experience of 7.3 years. Each test person performed one test for each of the four scenarios. From these 46 test persons 42 where able to finish all our tests. The remaining four persons needed to drop out due to simulator sickness at various stages of the test. For three of them a partial evaluation of their results was done. Before the start of our tests the participants weren't familiar with the test scenarios and the failures.

Measurement

We observed the reactions of all test persons on the given scenarios as well as the influence of acoustic and visual warnings. To prevent the test persons from having expectations during the test runs, each subject was only warned during one of the four scenarios. To prevent coherent results and succession effects, we changed the order of the various tests between different test persons. Furthermore the appearance of the warning was varied for different test persons.

The tests themselves started with a questionnaire and an initial trial run to get familiar with the simulator. Afterwards the respective scenarios started. During these scenarios the test persons committed thoughts and feelings using the think-aloud-method [11]. We combined these protocols with the observation how the test persons reacted inside the simulation and what result (accident or no accident) concluded. For doing so we used a simple coding scheme (Did the driver notice anything is wrong? Did the driver brake? Did the driver try to move the car to the sideline? Did an accident occur?). This allowed us to determine if the test persons correctly recognized the situation and if accidents could be avoided. We also looked closely on the health condition of the test persons in order to prevent negative influence due to simulator sickness [12]. In case of simulator sickness, a short break was scheduled and the test was either repeated aborted.

Warnings

Three different types of warnings are mainly used in current automotive and related research: visual, acoustic and haptic warnings. In general visual warnings are displayed on the head-up display (HUD) of the vehicle to inform the driver about possible critical situations. The size and position of the warning sign on the HUD is of great importance because of its influence on the reaction of the driver. An Evaluation of size and position of visual warning signs and their effect on the driver has been performed in [13]. Acoustic signals are also frequently used in current vehicles to direct the attention of the driver to critical situations. In this case duration and frequency of the acoustic warning signal are the decisive factors for the success of the warning. In [13] an analysis of different acoustic signals with different length and frequencies has also been performed to observe how different test persons react on such signals in critical situations. The third type of warning signals, which is used in vehicles, are so called haptic warnings. In

this case the driver is for instance warned through tactile vibration of the steering wheel during his drive. In current vehicles this is for instance used for lane tracking support in case the driver is about to leave his current lane [14]. Following the previous research we selected visual and acoustic warnings for this experiment. The acoustic warning was a sine tone with the duration of one second and a frequency of 1320 Hz which was repeated 4 times. The visual warning was provided as a red triangle with a black exclamation mark inside. It was presented virtually inside the projection of the simulation scene as a head-up display warning. Additional instructions were not given to avoid influences to the subject's reaction.

RESULTS

Due to our observations the majority of test persons were able to determine the particular situation or failure in each of the four scenarios. We observed the highest rate of correct detection in the ASIL A scenario. This is mostly due this being the least severe scenario which also does not require a sudden reaction by the driver. 94.1% perceived this situation correctly. Regarding the other three (more critical) scenarios, we observed a higher rate of misinterpretations. We see the reason for this higher rate in the fact that these situations require a much faster reaction of the driver which leads to greater attention on the task itself. One example can be seen in the circumstances that several test persons failed to notice the fact that the vehicle accelerated by itself in the ASIL B scenario. They blamed a failure of breaking for the fact that the vehicle didn't slow down and didn't notice that the vehicle even accelerated. In the ASIL C scenario most wrong determinations resulted from problems of some test persons to track the lane while driving with high speed.
At first glance it appears that the provided warning has not improved the correct determination of the provided situation. This is due to the fact that most test persons already stopped the vehicle in safe place immediately after the warning was provided. Hence the test persons were not able to correctly determine the situation since they reacted on the warning before the situation itself manifested. By sorting out these occurrences, we observed the results shown in figure 1.

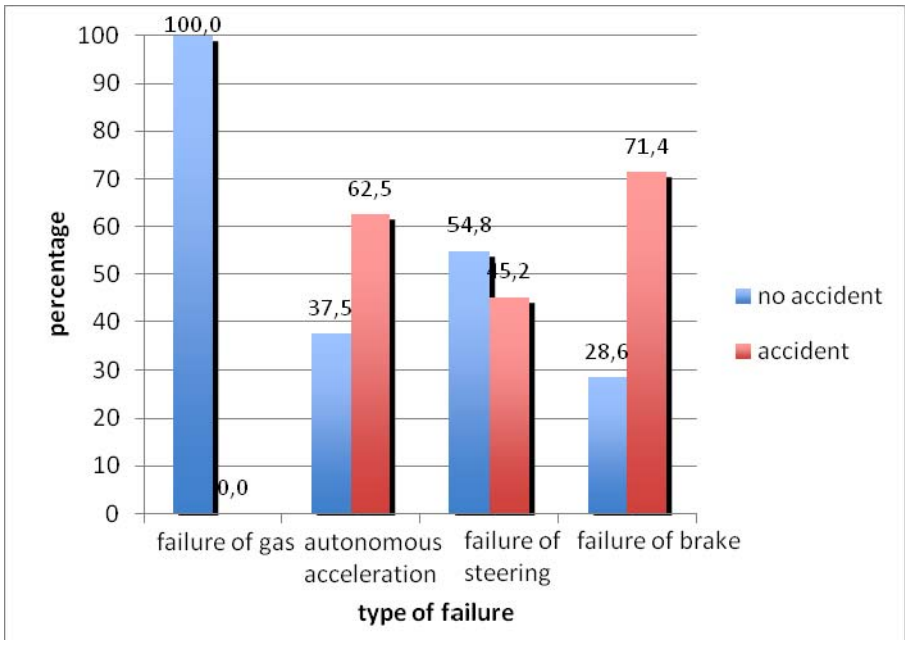

Figure1. Observed reactions of the test persons without a warning

We observed a correct determination rate of 100% in ASIL A (10 out of 10) and ASIL C (7 out of 7). In ASIL B and ASIL D these rates were lower with 82% (9 out of 11) and 87% (7 out of 8) respectively. Therefore it can be assumed that the provided warning had a positive influence on the number of correct determinations although the number of results led to this not being provable by our tests.

The second focal point for our research was how the persons reacted in these situations with regard to prevent harm for themselves and other traffic participants. At first we observed the occurrence of accidents in test runs without a warning before the respective situation. We predicted that the rate of accidents would increase according to the rising severity of the various scenarios. This prediction proved correct in general with 0% accidents in scenario ASIL A while ASIL B, ASIL C and ASIL D led to 62.5%, 42.2% and 71.4% accidents, respectively.

By the inclusion of an error warning before the occurrence of the situation we could reduce the number of accidents in general as shown in figure 2. ASIL B went down from 62.5% to 50% and ASIL D from 71.4% to 55.6%. ASIL C however suffered an increase in the number of accidents to 45.5%.

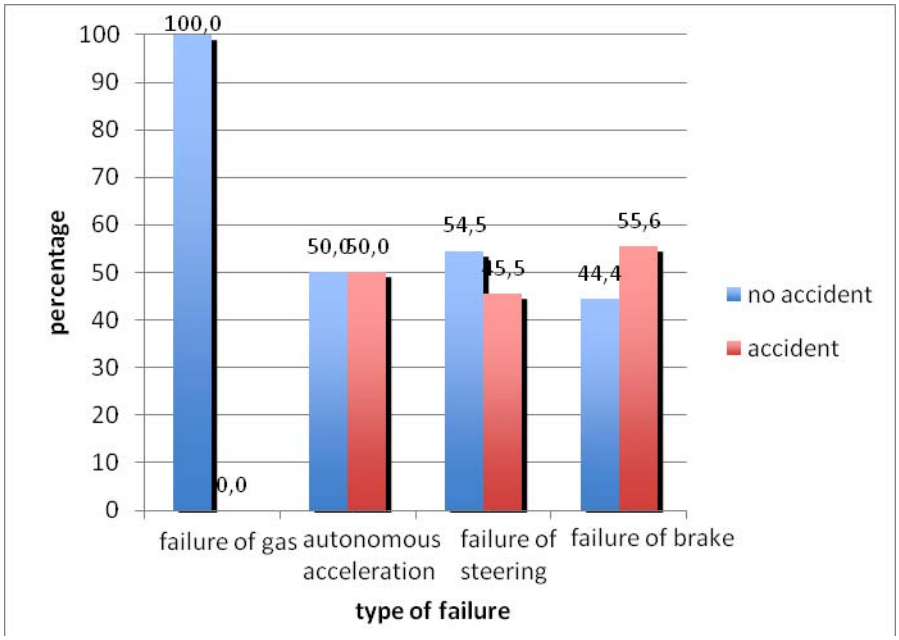

Figure2. Observed reactions of the test persons supported by a warning

This better overall performance is supported by the fact that some test persons almost instantly reacted on the warning by turning on the hazard lights and trying to stop their vehicle in a safe place. The overall attentiveness was also increased since the test persons were more concentrated on determining the reason for the failure. This became most obvious due to the think-aloud-tests. However avoiding an accident was still dependant on the skill of the driver in these sudden occurrences of critical situations as observed in ASIL B scenario. Although traffic density and average speed was rather low for the ASIL B scenario, because of strictly urban traffic, this rather high percentage of accidents had not been expected first. The main reason therefore was that many of the test persons were quite startled of this situation which often led to uncontrolled steering to avoid collisions, because of the decreased braking effect (according to the acceleration of the vehicle). Those who were able to control the car properly, for instance by activating the emergency brake and shifting down the engine, could avoid accidents because they remained concentrated. As this is a situation that rather does not seem likely, the reaction of most of the test persons is not surprising in the end because of its rather sudden appearance in compare to the ASIL A scenario. The results from the think aloud test revealed a general inhibition of the positive warning effect if the expected failure from a warning does not match the failure situation. In the think aloud test and the interview after the simulator study, those drivers reported that it leads to surprise and confusion and therefore to the inadequate reaction. This also applies if the driver is not able to derive a reaction strategy from the given warning, e.g. if the warning is missed, unspecific, appears too early or late or leads interpretation to a wrong system (brake vs. steering). Beside the slight decrease in the statistical numbers it could be observed that the severity of the accidents which still happened decreased. The increase in overall driver attentiveness led to better reaction even if an accident could not been avoided.

Overall the evaluation shows that a preceding warning decreased the amount of accidents or at least their severity. Further research questions were related to the design of the warnings. In summary, the chosen warning design was reflected as appropriate and helpful. Nevertheless, the test drivers suggested additional clear advice for an appropriate reaction strategy (e.g. stop the car immediately).

Inferential Statistics

First of all it was tested if the assumed hypothesis, that a preceding warning affects the number of correct determinations of each situation, could be verified. Therefore a chi square test was performed and the contingency table was created for each of the four observed scenarios regarding the warning condition and the determination condition. As some of the test persons were not able to determine the actual situation according to their immediate reaction on the warning, these test persons were excluded for the chi squared test to gather the correct values. This has been performed for each scenario to verify if the features warning condition and determination condition are stochastically independent.

As each value is lower than the critical value of the chi squared test of 3.841 [15], it could not be verified that the samples differ significantly. Therefore it could not initially be stated that the provision of a preceding warning influences the correct determination of a certain scenario. To prove if the calculated value was just received randomly according to the samples, the p-values for each scenario were calculated as seen in table 2: Failure of gas (p=0.5), autonomous acceleration (p=0.48), failure of steering (p=0.37) and failure of brake (p=0.47).

Table2.

Chi squared values by scenario

Scenario	Chi Squared Value
failure of gas	0.0
autonomous acceleration	0.057
failure of steering	0.48
failure of brake	0.103

Afterwards it was proven if the assumed hypothesis, that a preceding warning has a positive effect on the reaction of the driver, could be verified. As for the verification of the previous hypothesis, the contingency table was created for each of the four scenarios, regarding the warning condition and the accident condition. According to this the chi squared values were calculated for each scenario to verify if the two observed features are stochastically independent. As each value is lower than the critical value of the chi squared test of 3.841 it could not be verified that the samples differ significantly. Because of that it could not initially be stated that the provision of a preceding warning has a positive effect on the reaction of the driver. To prove if the calculated value was just received randomly according to the samples, the p-values for each scenario were calculated: Failure of gas (p=0.5), autonomous acceleration (p=0.375), failure of steering (p=0.49) and failure of brake (p=0.304).

CONCLUSIONS

The evaluation of the performed tests has provided interesting results for security related considerations for present and upcoming x-by wire systems. However, a critical discussion of these results is needed.
First of all the test setup does not precisely reflect the feeling of real driving. This is due to the use of a driving simulator and its properties such as the missing movement of the body and limited field of view provided for the test persons. Therefore they may lack the ability to judge the overall traffic situation. Beside this general limitations the wrong interpretation of the failure in our study may have an important effect on the results. It might happen that a test person attributes the failure (e.g. engine stop) rather to the simulation itself than to the vehicle in the simulation. We implemented engine sound and the real dashboard (incl. warning lights) to avoid a misattribution. Additionally we asked the test subjects during (think-aloud test) and after the tests about their thoughts about the failures. All of them reported that they were confident that the failure was a part of the test and in time critical scenarios they did not reason the cause of failure. We also observed some oddities in the behavior of the computer-controlled traffic.

The test track we used in our driving simulator proved to be appropriate for our evaluation as it included all necessary properties of our test scenarios.
The think-aloud-test we used to gather information about feelings and thoughts of the test persons has been discussed in recent literature. One source [16] points out the unnatural process which could change the demands of the task. This could imply for instance that the test persons believe that they have to fulfill certain expectations which could lead to a distortion of the results. Nevertheless it provided appropriate results for the purpose of the evaluation while different variations could be used to reduce such negative impact.
While the amount of tests persons is appropriate for a first test, the results presented here are not statistically provable but reveal tendencies and qualitative results for further studies.

ACKNOWLEDGMENTS

This work was partly supported by German Research Foundation, project ORCHideas (DFG GZ: 863/4-1).

This work was also partly supported by European Research Foundation, project SAVELEC (Safe control of non cooperative vehicles through electromagnetic means, FP7- SEC-2011, Grant Agreement Number 285202).

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