Avoiding Electromagnetic Interference Induced Risks for Autonomous Driving

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***Abstract*—Autonomous vehicles require an extremely high safety level, whereas their functionality is based on a high density of electronic components and sensing systems. As a consequence, electromagnetic compatibility does not only become even more challenging than usual in electronics development, but the influence of unintended and intended electromagnetic interferences must also be assessed under future autonomous driving level 3 to 5 scenarios, which differ significantly from today's ones. In this work, an overview is provided of the possible interference sources that need to be taken into account. Currently used electromagnetic immunity tests are described for two specific automotive components. It is explained where these methods require improving to adapt to the enhanced requirements of automated driving and how this future-proofing can be achieved.**

***Index Terms*—electromagnetic compatibility, autonomous driving, electromagnetic interference, power electronics, artificial intelligence**

I. Introduction

Autonomous driving (AD) and vehicle electrification determine the future frame conditions for competition in the automotive industry. Both technical trends require fundamental progress on guaranteeing electromagnetic compatibility (EMC) at both component and vehicle level [1]. In particular, immunity is needed against electromagnetic interference (EMI) caused by the vehicle itself, as well as against external interferences, including intended electromagnetic interference (IEMI) as part of criminal activities.

With increasing automated driving level of a vehicle [2], the number of implemented safety and comfort related driving functions and the number of vehicular system states increase rapidly, which in turn strongly impacts the complexity and effort of EMC testing. At the simplest level, a sensor affected by (I)EMI could provide wrong, delayed or no data at all to an electronic control unit (ECU) that depends on its feedback, thereby affecting its decision making process, possibly leading to unintended actions or dangerous manoeuvres [3].

At the level of the vehicle, the vast number of EMC test iterations required to guarantee safe and reliable automated driving thus asks for a different approach. It is expected that a combination of standard established EMC tests with virtual tests, based on validated numerical models and simulations, could provide a great win in time and effort. Furthermore, such EMC test results can then be used for the training of artificial intelligence (AI) methods with the aim to extract hidden dependencies between system parameters and the resulting EMC behaviour. This enables predictions of the impact on EMC of planned technical alterations during a product's development phase.

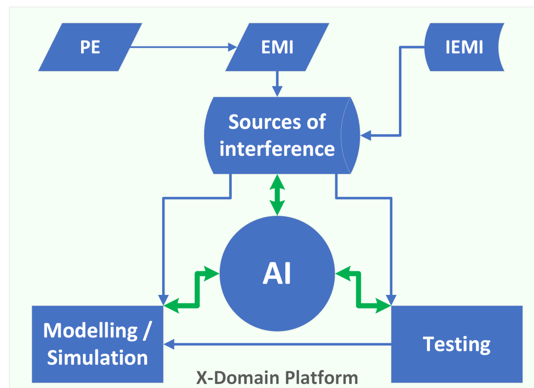

Figure 1: Process overview for the improvement of automotive electromagnetic immunity, incorporating modern power electronics as a source of EMI, and the AI-supported evaluation of the synergies between modelling, numerical simulations and physical tests.

Vehicle electrification enables a manifold of applications, including those that require high electrical power. Modern electrical systems can be distributed all over the vehicle due to their relatively small form factor and the abundance of power supply lines throughout the vehicle. Several of these systems temporarily require high currents as part of their standard operation, during which their supply lines can generate magnetic field disturbances in nearby systems. These magnetic fields can either induce currents in nearby cabling or directly affect systems that include passive, permanent magnetic elements, such as the magnetoresistive sensors used in automotive tra-

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jectory, angle, current and magnetic field measurements [4]. An additional EMC challenge that originates from increased vehicle electrification is conducted EMI caused by switching transients of the various power converters used throughout the modern vehicle.

The aim of the research reported in this paper is to achieve a multi-factorial engineering approach adapted to current automotive developments in order to improve and facilitate the electromagnetic immunity of automotive components and (sub-)systems. This includes the study of modern interference sources, e.g., due to power electronics (PE) or malicious attacks. First, a systematic evaluation of the test requirements for current and future AD components and systems is to be carried out. Based on these results, potential gaps in existing EMC standards and methods must be identified and closed, e.g. extended by new or adapted virtual tests and subsequently combined into an AI-based analysis methodology, as schematically represented in FIGURE 1.

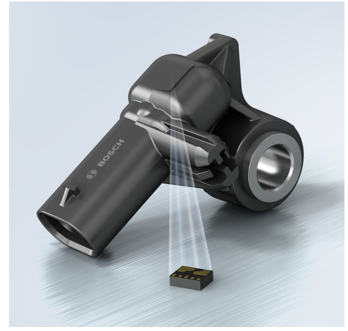
II. BACKGROUND

A. Devices under test

Two exemplary automotive components used in current automated driving and evolving into AD systems are an acceleration sensor shown in FIGURE 2a and an electric power steering unit in FIGURE 2b. The former is mainly designed for impact detection, whereas the latter controls and assists the vehicle steering.

The two-channel peripheral accelerometer that will be used as a device-under-test (DUT) in this study provides information on direction and level of impact by measuring accelerations along two spatial axes. Such accelerometers are installed at more than twenty locations in a typical vehicle, e.g., mounted at the various sides and crumple zones of the vehicle to improve impact detection and airbag deployment as well as near the wheels for active suspension to enhance driving comfort. The accelerometer contains a micromechanical sensor element comprising fixed and moving finger structures and spring pins. The seismic mass with its comb-like electrodes is resiliently suspended in the metering cell. A linear acceleration in the sensing direction changes the distance between the moving and fixed structures, which alters the overall capacitance [5]. The associated measured electronic signal is then amplified, filtered and digitized by an application-specific integrated circuit and transmitted to an ECU over a single pair of insulated copper wires.

The second DUT in this study is a modular built electric power steering unit that supports advanced driver assistance functions (ADAS), in which an electric servomotor converts a torque via a worm gear and transfers it to the steering rack by a pinion. Such unit has among the strictest requirements for electromagnetic compatibility and immunity. In the electric power steering system, a torque sensor on the steering pinion measures the torque that the driver applies to the steering wheel. Based on these data, the electronic control unit calculates the steering assistance, which the electric motor needs to apply. A magnetic pole wheel is fitted on the input shaft that is connected to the steering pinion by means of a torsion bar. When a driver applies torque to the steering wheel, the torsion bar is rotated and, in turn, the magnets' relative positions to the sensor are altered, changing its magnetoresistance [6].



(a) Accelerometer

(b) Electric power steering unit

FIGURE 2: DEVICES UNDER TEST USED AS EXEMPLARY AD COMPONENTS IN THE EMC STUDY. © ROBERT BOSCH GMBH

B. EMC requirements by manufacturers

International EMC standards exist for most electronic, electric and electromechanical equipment, in particular for consumer products, such as for road vehicles and their corresponding (sub-)systems and components [7]. Automotive original equipment manufacturers (OEMs) impose additional test requirements on their Tier-1 suppliers based on their market and customer-specific needs. These typically extend the frequency range and the amplitude of the interference signals for those tests, decrease the frequency step width, and eventually add specific signal modulations, thus increasing the test effort in both cost and time.

As part of the work presented here to understand the impact of EMC test requirements for current and future AD components on existing EMC standards and methods, such additional OEM requirements were analyzed for approx. 50 automotive OEMs for three common EMC test methodologies, namely bulk current injection (BCI), radiated immunity portable transmitter (RIP), and radiated immunity (RI). In this paper the focus of the requirement analysis is on BCI, as a crucial test methodology to investigate the effects of EMI induced by novel PE components introduced for vehicle electrification [8].

FIGURE 3 provides an overview of the OEM-specific requirements for BCI current levels at selected frequencies for both open and closed loop tests, represented by a boxplot that is confined by the 25th and 75th percentiles. Moreover, all outliers are displayed as individual symbols, further highlighting the large spread in individual OEM requirements. In comparison, the BCI currents for the lowest test severity level, provided in the standard from the safety electronics working group of the German Association of the Automotive Industry, are shown as a dashed line [9]. As these are minimum requirements, these levels mostly correspond with the lower ends of the boxes in FIGURE 3.

Parts of the observed spread and the higher BCI current levels in the OEM requirements are thus due to increased electromagnetic immunity targets depending on the safety criticality of the same OEM's component class, typically increasing 6 dB with function reliability needs. Nevertheless, for various test frequencies, i.e. 1, 30 and 400 MHz, the displayed spread is multiple orders of magnitude larger, up to 73 dB. Subsequently, this requires signal generation and measurement equipment with extensive dynamic ranges, possibly demanding additional power amplifiers. More specifically for BCI-based EMC measurements, the injection and monitoring probes are limited in power and frequency range, thus potentially requiring a physical exchange during an EMC test sequence, adding further to the test's duration, effort and cost.

Therefore, for EMC testing in general, an intelligent, reduced selection of the most relevant EMC parameters is expected to provide large benefits, which can then be further adapted to the manufacturer's or customer's need. As envisioned in the research presented here, such selection could be based on the AI-supported analysis of physical tests combined with numerical simulation results that are based on established DUT-models. This is expected to enable the prediction of crucial measurement ranges for certain adaptations of a known EMC-compliant DUT or of its installation environment.

C. Complementary electromagnetic immunity test methods

Various electromagnetic immunity test methods have been developed during the last decades and are currently employed to verify the EMI immunity of DUTs. As mentioned before, those measurement approaches are defined in common international EMC standards, with generic or specific scopes, for example those developed for the automotive industry. The principal immunity test methods involve either an absorber-lined shielded enclosure (ALSE) also known as a semi-anechoic chamber (SAC), an open-area test site (OATS), a BCI, a stripline, a gigahertz transverse electromagnetic (GTEM) cell or an electromagnetic reverberation chamber (RC), each with its advantages and disadvantages. The ALSE method is by far the most widespread within the EMC community, as the required SAC is also used for other common EMC tests, in particular for those involving radiated emissions. Hence, extensive literature exists for immunity tests of automotive equipment employing the ALSE methodology, as well as for comparisons of various immunity test setups [10]–[13].

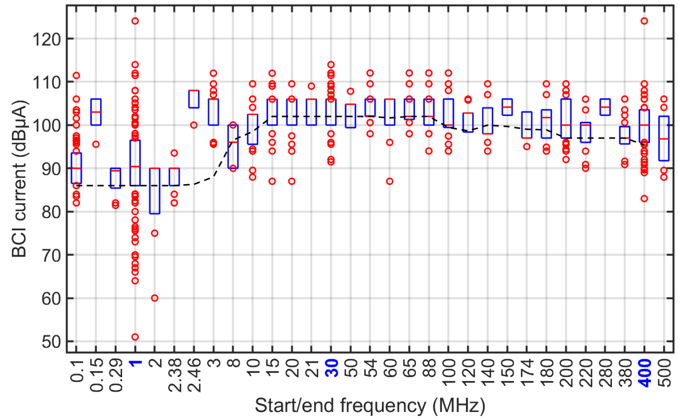


FIGURE 3: BOXPLOT OVERVIEW OF THE VARIATION IN BCI CURRENT REQUIREMENTS BY OEMS FOR VARIOUS SPECIFIED START AND END FREQUENCIES. ON EACH BOX, THE HORIZONTAL RED MARK INDICATES THE MEDIAN, AND THE BOTTOM AND TOP EDGES OF THE BOX INDICATE THE 25TH AND 75TH PERCENTILES, RESPECTIVELY. OUTLIERS ARE PLOTTED AS INDIVIDUAL SYMBOLS. THE DASHED LINE REPRESENTS BCI TEST PARAMETERS FOR THE AK-LV27-VALIDATION OF LEVEL-1 DUTS [9].

Investment in an ALSE is cost-inefficient if it is intended to only be used for immunity tests of automotive components [13]. On the other hand, both BCI and stripline methods are limited in their usable frequency range [14], [15]. The main disadvantage of GTEM cells is their volume limitation and its impact on maximum DUT size [16]. As for the OATS, the main disadvantages are quite obvious [17]: the dependency on weather conditions, the possible RF interference from the external environment and the possible public exposure of confidential test sequences. Recently, the RC is gaining appreciation as an electromagnetic immunity test approach, because it lacks some of the above mentioned disadvantages. As a consequence, corresponding immunity test standards, e.g., ISO 11452-11, have been published more than 15 years after those for other methodologies. The RC's advantages comprise a full shielding with respect to the environment, the reduction of the RF power required for an equivalent E-field strength, the large frequency interval supported that is only bounded from below by the RC's lowest usable frequency (LUF), which depends on the RC's dimensions (for RC dimensions of about 1x1x1 m, a LUF of approx. 1 GHz is obtained), and the reduction in measurement time as inside an RC the DUT is simultaneously illuminated from all sides and with multiple E-field polarities [18], which might also result in a reduction of uncertainty. However, in an RC it is impossible to study an entirely defined irradiation situation and results need to be validated on a statistical base.

III. EMI CAUSED BY ON-BOARD POWER ELECTRONICS

PE systems are used in electric vehicles (EV) in applications such as drive inverters, on-board chargers and DC/DC converters and are subject to strict specifications [19]. Their weight and volume are largely determined by passive components such as transformers, inductors, filters, capacitors

TABLE I: PHYSICAL CHARACTERISTICS OF SI, 4H-SIC AND GAN SEMICONDUCTORS. ADAPTED FROM [20].

Parameter	Unit	GaN	4H-SiC	Si
Bandgap, E_g	eV	3.45	3.26	1.12
Electrical breakdown field, E_c	kV/cm	2000	2200	300
Electrical mobility, μ_n	$\mathrm{cm}^2/\mathrm{V{\cdot}s}$	1250	1000	1500
Hole mobility, μ_h	$\mathrm{cm}^2/\mathrm{V{\cdot}s}$	850	115	600
Saturated electron drift velocity, v_{sat}	$\cdot 10^7$cm/s	2.2	2	1
Thermal conductivity, λ	W/cm·K	1.3	4.9	1.5

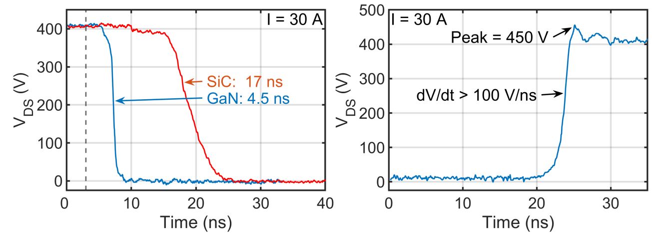
and heat sinks for the semiconductors. The use of smaller passive components is possible by increasing the switching frequency, but this also increases the losses in the switching components. The latter problem can be mitigated by using wide-bandgap (WBG) power semiconductors, such as SiC or GaN instead of Si devices. These WBG semiconductors have various advantageous physical properties compared to their silicon counterparts, which are summarised in TABLE 1 [20]. The electrical properties of SiC and GaN result in a lower on-resistance and thus in lower conduction losses, which enable higher switching rates, with GaN devices being up to four times faster than SiC-based switches, as shown in FIGURE 4a.

As part of the research presented here, the interference potential of PE components within an EV's electrical system is investigated. The effects can generally be categorised into three groups:

a Annoying effects, e.g., disturbance in radio transmission or display function, strobing LED's, etc.
b Disturbing effects, e.g., sudden reset or disturbance of on-board digital equipment, changes in input/output (I/O) data status, etc.
c Catastrophic effects, e.g., loss of control of operational sections or data, failure of electronic components, change of threshold settings, catastrophic failure/accident, etc.

In a typical EV, several systems utilise PE circuits: one or more traction converters, an on-board charger as a controlled rectifier, and various isolating or non-isolating DC/DC converters for the on-board power supply with different voltages. For the drive or traction inverters of such EVs, the switching frequencies are mostly of moderate magnitude. Furthermore, because of the parasitic capacitances of the stator windings and because of the risk of partial discharge, high rise times ($\frac{\partial u}{\partial t}$ values) should be avoided from an EMC point of view. The recommendation for standard stators is 5 V/ns, which is orders of magnitude below the range that can be achieved with WBG power semiconductors (>100 V/ns), as shown in FIGURE 4b. Combined with the fact that mitigating measures are achieved with little to moderate effort, EMI emitted by drive converters and the effects on AD are not the main focus of the research presented here. Furthermore, as on-board chargers are not in charging mode whilst driving, they are also regarded as less relevant to this study.

Isolating DC/DC converters use a transformer to achieve galvanic isolation, which on the one hand has a beneficial effect on the transients (inductive base load for low load commutation), on the other hand, however, might produce EMI with the transformer acting as an antenna. A *worst case*-scenario is examined in this study, namely investigating what challenges arise with extremely steep rise times. Non-isolating DC/DC converters with fast-switching semiconductors and therefore extremely fast-switching times as a source of interference are particularly well suited for this, with those using WBG semiconductors generating very steep transients in hard switching mode.



(a) Fall time GaN vs. SiC (b) Rise time GaN-FET

FIGURE 4: HARD SWITCHING PERFORMANCE OF WBG POWER DEVICES, WITH A) THE COMPARISON OF FALL TIMES OF GAN VERSUS SIC DEVICES, WITH THE FORMER BEING FOUR TIMES FASTER, AND B) THE STEEP RISE TIME OF A GAN-FET. ADAPTED FROM [21].

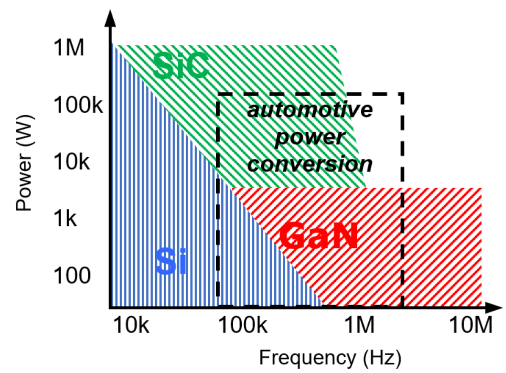


FIGURE 5: PERFORMANCE OF GAN, SIC AND SI-SEMICONDUCTORS USED IN AUTOMOTIVE PE DEVICES.

SiC and GaN devices have the potential to enhance the performance of PE in EVs, as they are able to operate at higher switching frequencies with overall lower losses than those of traditional silicon devices, as shown in FIGURE 5. Autonomous EVs can benefit from the use of SiC or GaN FETs in on-board PE systems, as using high switching frequencies has a positive effect on the efficiency and power density of the systems. Additionally, unlike Si- and SiC-based devices, GaN transistors do not have a body diode in their structure, so they lack blocking delay losses.

WBG power semiconductor devices, their potential and their rational use for efficient electric energy transformations have been well investigated [22], and the advantages of GaN semiconductors over SiC- and Si-based devices for the switching in different DC/DC converters in EV applications has been evaluated by comparing their total switching losses [23]. Based on the above investigations, two types of WBG devices are developed in different DC/DC converters of two I/O voltage ranges with switching frequencies up to approx. 1 MHz, which requires the observation of best layout practises and PCB design guidelines [24]. The two converters under consideration are:

1) from 200–480 V to 48 V based on SiC and/or GaN devices
2) from 48 V to 12 V based on GaN devices

It is expected that 48 V converters will become increasingly predominant in future vehicles, and that GaN technology will become attractive for the conversion of 48 V to 12 V and vice versa. Hence, it is necessary to take the associated additional EMC challenges into account, with the very high transients of up to 100 V/ns posing a particular challenge. These transient's slopes and additional resonances due to parasitic inductances and capacitances in the device can produce considerable conducted and radiated EMI at frequencies up to the low gigahertz range, depending on the specified accepted levels and safety margins.

WBG-devices as EMI noise sources have been investigated before [25], [26], however, the important question of the magnitude and influence of electromagnetic emissions stemming from WBG-semiconductors in autonomous EVs seems not to be adequately considered in the literature so far, although the EMC properties of DC/DC converters used in EVs, which could influence sensors and other devices vital for the overall reliability of the system, are of utmost importance.

As a next step, new EMI/EMC challenges emanating from the use of WBG technology in EV DC/DC converters will be examined and quantified. Utilising WBG circuitry, EMI/EMC will be considered as well, investigating possibilities to avoid potential interference at the source or to minimize its propagation within the vehicular system, primarily focusing on conducted emissions. Nevertheless, with increasing PE device switching frequency and rise time, the risk of radiated EMI increases rapidly, hence the shielding of assemblies, cables and connectors will require additional attention.

IV. IEMI BY AD-RELEVANT HIGH POWER ELECTROMAGNETICS

IEMI threat scenarios have been characterized in the literature in terms of the classes in which their sources can be divided; their impact, performance and efficiency; and their likelihood to occur in the typical environment of a DUT or system under test [27]. It was concluded that criminal attacks executed by small groups or individuals are expected to be limited to constructions for electromagnetic wave emulation that are low-cost; small-sized; highly mobile; require little expertise in design and operation; and have a high component availability. Hence, their main modules typically constitute a high-power impulse source, an RF-modulator and a matching antenna. For the generation of effective ultra-wideband (UWB) pulses this involves a large capacitor, a spark-gap and an antenna that also serves as resonator, as shown in FIGURE 6.

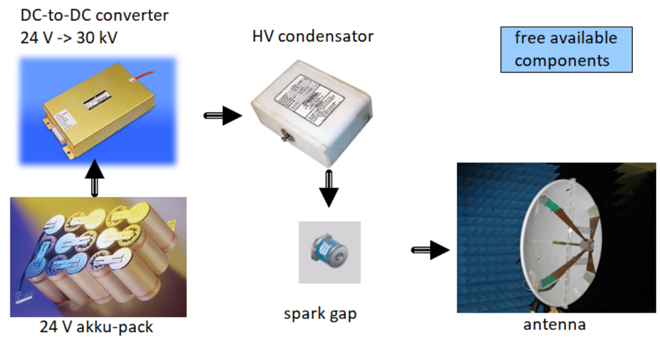


FIGURE 6: TYPICAL COMPONENTS FOR THE ASSEMBLY OF A SIMPLE UWB-BASED IEMI SOURCE. © WIS[1]

The high power electromagnetic (HPEM) capabilities at the Bundeswehr Research Institute for Protective Technologies and CBRN Protection (WIS[1]) in Munster are specifically tasked to investigate the disruptive effect of HPEM attacks. A variety of indoor and outdoor facilities exists for the simulation of attacks with (non-)nuclear electric pulses, which are of particular interest for investigating the effects of attacks on autonomous vehicles. Among others, a high-power microwave-generator for the frequency range of 0.675–3 GHz and a maximum power of 500 MW (FIGURE 7a and FIGURE 7b), a GTEM-chamber for the frequency range of 0–18 GHz operated at 50 kV, UWB pulse generators, wideband antenna systems and open waveguides are employed.

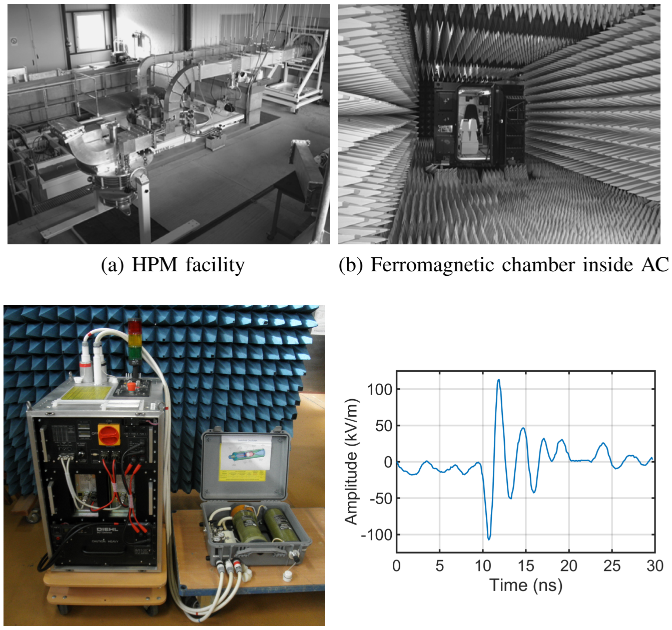
As mentioned above, UWB pulse-generators in combination with dedicated antenna systems are of particular interest. The pulse generators at WIS allow adjusting the pulse rise time and pulse duration. To avoid damage to the DUT, the intensity is adjusted by placing a damper between the pulse-generator and the antenna or by increasing the distance between the antenna and the DUT. As a very direct and powerful test method, a *Diehl suitcase* (FIGURE 7c) is available at WIS, deliberately constructed to reproduce plausible IEMI-attacks. The corresponding waveform for a typical HPEM-pulse at 1 m distance from a Diehl DS-110 generator is displayed in FIGURE 7d [28].

V. AI-BASED EMC DEVELOPMENT AND ANALYSIS

Currently, the capacity of methods from AI are tested in many research and application fields to control industrial processes, including the design of new industrial components, e.g., for applications to enhance electronic design automation [29]–[32]. This includes the study of the potential of AI methods to improve the EMC properties of autonomous devices and their resilience to (I)EMI.

The term *artificial intelligence* has various definitions and a diffuse extension. Within this work, the focus is on machine learning (ML) processes. In an engineering context, ML is usually considered as the behaviour of agents which obtain

[1]WIS is a departmental research institute of the German Federal government and is subordinate to the Federal Office of Bundeswehr Equipment, Information Technology and In-Service Support (BAAINBw).



(a) HPM facility (b) Ferromagnetic chamber inside AC

(c) *Diehl suitcase* with external power supply (d) DS-110 waveform at 1 m distance. Adapted from [28].

FIGURE 7: HPEM CAPABILITIES FOR IEMI TESTS AT WIS. © WIS[1]

feedback from their environment (via sensors) and optimize their output (e.g., the action of particular actors) according to a calculable score or metric. These ML methods include the identification of parametric models, such as support vector machines, deep neural networks and, particularly, more sophisticated methods such as convolutional neural networks, transfer learning or reinforcement learning [33].

In contrast to many fields of data analytics, data usually do not arise abundantly in an engineering context and particular methods for their allocation have to be developed. To learn from the performance of previous designs, measurements of their performance can be used for the assignment of labels to parametric representations of EMC-relevant design parameters. This enables a supervised learning process as usually employed in regression processes, to create models that allow for the prediction of new designs or for classification of suitable and improper designs. If insufficient data are available, simulations can replace legacy data to provide labels for design proposals. However, such simulations have to be designed to capture the behaviour of the system sufficiently accurate and they must be inexpensive as well. To this end, multi-physical simulation is part of the overarching *cross-domain* (X-domain) platform indicated in FIGURE 1. In a mature state, the simulation can qualify to be part of a *digital twin* of an AD vehicle representing its EMC-relevant parts. In connection to such digital twin, the role of AI is not restricted to parameter identification, but can also become a part of the digital twin to model functions that are difficult to capture by physical modelling.

Classical ML procedures drive the identification of a model's internal parameters by minimizing the discrepancy of the model output to labels provided to the learning data, which are either measured in a suitable metric (supervised learning) as used for regression or classification problems, or by clustering the data according to certain rules (unsupervised learning). On the other hand, reinforcement learning resorts to a score that is assigned to the perceived environment and needs no direct labeling of its output. Then a *policy prediction* of how to interact with the environment is permanently adapted to maximize this score based on a Bellman equation [33]. To predict the impact of changes of the environment on this score, usually deep neural networks are employed, which are often more adequate for industrial as well as design processes, and hence part of the research presented here. In particular, this avoids the expensive process of labeling and reduces the amount of required data.

VI. CONCLUSIONS

This paper presents the proposed steps to enhance electromagnetic immunity of autonomous and electrified vehicles. It is explained that vehicular acceleration sensors and the electrical power steering sub-system are of particular interest as automotive DUTs, and that modern EMC test methods such as the RC can be used as a faster test practice, which involves the investigation of well-defined, simultaneous irradiation of DUTs with multiple E-field polarities on a statistical base. Power electronic components are shown to become much more prevalent in future EVs, hence their impact as EMI sources needs to be studied with particular attention. To this extent, new wide-bandgap semiconductor-based devices with increased switching rates are being introduced in DC/DC-converters in order to determine the effects of their transients on automotive DUTs. Further interference studies on these DUTs involve HPEM IEMI signals caused by plausible criminal techniques.

The synergies between modelling, numerical simulations and physical tests will be evaluated by means of an AI-methodology based on ML processes. This supports the aim of this research to achieve a multi-factorial engineering approach adapted to current automotive developments that improves the electromagnetic immunity of automotive components and (sub-)systems.

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