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Assessment of low frequency magnetic fields in electrified vehicles

Trentadue, G., Zanni, M., Martini, G.

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Contact information
Name: Giorgio Martini
Address: European Commission, Joint Research Centre, Vie E. Fermi 2749, I-21027, Ispra (VA) — Italy
Email: Giorgio.martini@ec.europa.eu
Tel.: +39 0332 789293

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Contents

Abstract

This report presents exploratory research into the low frequency (up to 400 kHz) magnetic fields generated by hybrid and electric vehicles under driving and charging conditions.

The study includes a literature survey and experimental work addressing the issues of: measurement protocols; instrument selection; and data processing, with the aim of contributing to standards development. When the experimental activities were planned, there were no published measurement procedures specific to the automotive sector; so different methodologies and instrumentation setups were explored.

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Authors

Trentadue Germana, Joint Research Center

Zanni Marco, Joint Research Center

Martini Giorgio, Joint Research Center

1 Executive summary

Electrification is currently considered one of the key options for decarbonisation of the road transport sector. The number of registered electric vehicles and of models offered on the market is continuously increasing.

Still, there are a number of issues that represent, or are perceived by consumers as, barriers to the purchase of an electric car. Limited range, high price, and lack of recharging infrastructure are the most important ones. Potential safety hazards related to exposure to magnetic fields during the use of electric vehicles are in some cases indicated as a reason for concern that can discourage people from choosing this technology.

The health effects of electromagnetic fields have been studied for several decades and there is no clear evidence of possible long-term effects. On the contrary, direct physiological effects are well known. Direct effects occur above certain thresholds and consist of electrostimulation of nerves at low frequencies (1 Hz to 10 MHz) and heating of body tissues at higher frequencies (100 kHz-300 GHz). Indirect effects are also known and include: initiation of electro-explosive devices, electric shocks or burns due to contact currents, projectile risk from ferromagnetic objects, interference with medical devices, etc.

Direct effects are linked to in-body quantities, not measurable in practice. For these reasons the international guidelines published by the International Commission on Non-Ionizing Radiation Protection (ICNIRP) identify specific parameters to be measured, and define the related reference levels for workers and the general public.

While existing vehicle regulations address aspects such as electromagnetic compatibility and other safety related issues, for the moment there is no specific legislation regulating electromagnetic fields (EMFs) generated by vehicles. There are a few recently published procedures that are recommended to assess EMFs in the automotive sector which differ in the level of detail of the protocol description and certain requirements.

This study was carried out with the following objectives in mind:

- To provide a clear picture of current knowledge in this field by means of a comprehensive literature survey. A summary of the main findings is available in chapter 3.2;
- To gather experimental data on low frequency magnetic fields generated by electrified vehicles of the latest generation through ad-hoc experiments carried out in the JRC's VELA laboratories (section 5);
- To support the development of a standard test procedure in anticipation of future legislation on type approval of electric vehicles (sections 6, 7).

In total, nine different electrified passenger cars, including both pure electric vehicles and hybrids, were tested in the JRC's facilities. The main focus was the assessment of the magnetic flux density (B-field), in the time and frequency domains, inside the vehicle under various operating conditions. The instrument used for the campaign follows the guidelines set in IEC standard 61786-1:2013 "Measurement of DC Magnetic, AC Magnetic and AC Electric Fields from 1 Hz to 100 kHz with Regard to Exposure of Human Beings – Part 1: Requirements for measuring instruments".

It is important to stress that when this exploratory work started, no standard for the assessment of low frequency magnetic fields inside vehicles was available. As a consequence, the protocol used changed significantly in response to the experience gained in the course of the work. Measurement locations corresponding to different parts of the human body (head, thorax and feet) were defined inside each vehicle. The vehicles were operated according to a driving cycle that included hard acceleration and braking events, as well as constant speed phases. Being a completely new activity for the JRC, solutions to a number of technical challenges were found, in particular regarding reproducibility of the driving cycle and proper data acquisition.

Results show that the highest B-field values were recorded in locations corresponding to the feet positions, during hard accelerations and regenerative braking. Acceleration and braking phases, rather than constant speed phases, were responsible for the highest peaks of current and consequently B-field; B-field values were also influenced by vehicle configuration and use during the test (air conditioning, regenerative breaking).

The study has identified some potential issues related to the requirements of the instrumentation and the test procedure that have to be further investigated and solved in view of a future regulation.

A complete characterization of the magnetic fields arising during vehicle operation would require correlation of instantaneous B – field values with the currents in the conductors within the vehicle, and with the vehicle's speed. This task represents a significant challenge in terms of measurement instrumentation that has not yet been fully solved. Ad-hoc tools must be developed to acquire and synchronize all relevant parameters, including encrypted parameters from the vehicle's electronic control unit. Moreover, it turned out that the frequency resolution of probes appropriate for measuring human exposure to magnetic fields (i.e. probes complying with European Directive 2013/35/UE, ICNIRP 2010 and 1998 guidelines, and IEC 61786-2 -Measurement of DC magnetic, AC magnetic and AC electric fields from 1 Hz to 100 kHz with regard to exposure of human beings – Part 2: Basic standard for measurements) might not be sufficient for accurate frequency-domain characterisation of the field. This implies that specific requirements are needed for instruments to be used for measurements of exposure to magnetic fields inside vehicles. The other issue related to the instrument used is that raw B - field values were not available during time-domain measurements, since the probe only output the percentage of the ratio between the measured field and the reference level, limiting the possibilities for post-processing. For this reason, further measurements, whose results are pending publications, were made with a second instrument in collaboration with ENEA, the Italian Agency for New Technologies, Energy and Sustainable Economic Development, with the aim to acquire instantaneous magnetic field values to quantify a hypothesised underestimation of values recorded by the instrument used previously.

Recently published measurement procedures for magnetic fields inside vehicles recommend an approach similar to that described here in terms of used instrumentation and operating conditions of the vehicle under test. However, these protocols differ in the level of detail concerning both the procedure and the requirements for the instrumentation. An effort to harmonize and better define the so far proposed standards is desirable.

In a future with massively increased production of electric vehicles and inadequate regulation, manufacturers might seek to reduce production costs by saving on protections against EMF exposure, bringing car models with lower EMF safety standards to market. To prevent this, an appropriate regulatory standard, for type approval or in-use compliance, is required. This would also provide a clear legislative framework with which market players in the automotive sector could plan their investments with less uncertainty.

2 Introduction

Electrification of vehicle powertrains is no longer a pipe dream, but is already part of our present. Numbers are clear: there is a constant increase in availability of models from different brands and in different categories for a total number of registrations within the period 2010 – 2017 of 882081 electric M1 passenger cars, 55143 eLCV (light commercial vehicles N1), 173000 (M2-M3) buses [1]. Currently 33 PHEV (Plug –in Hybrid Electric Vehicle) models and 28 pure EV (Electric Vehicle) models are available on the market with new models continuously announced. Sales projections until 2050 foresee an EV market share of about 80%. The statistics confirm also that countries with policy oriented to high financial incentives experience the highest share of EV [1] on the road, highlighting that the higher EV price compared to conventional vehicles is one of the users' concerns together with limited driving range, performance and reliability over time, and recharging infrastructure availability.

2.1 Why does it make sense to measure electromagnetic fields in vehicles?

Exposure to electromagnetic fields (EMF) is one source of the anxiety and diffidence which consumers hold towards electrified vehicles. This issue has been already considered at different levels but not yet fully addressed. The question of whether or not EMF exposure is a health issue is a subject of heated discussions and worries, also among automakers about to make the huge investments required to enter the EV market. Extremely low-frequency (ELF) magnetic fields were classified as possibly carcinogenic in 2002 by the International Agency for Research on Cancer (IARC), but there is no scientifically robust evidence that confirms any correlation between exposure and adverse long-term health effects. Besides the potential impact of EMF exposure on human health, another concern is EMF interference with wearable or implanted medical devices such as pacemakers. Some citizens also claim electromagnetic hypersensitivity (EHS) and doubt whether it is safe for them to buy hybrid or electric vehicles, even if EHS has not so far been scientifically proven and is not a recognised medical condition. Moreover, the car industry is rapidly evolving with the integration of increasingly sophisticated systems, such as advanced driver-assistance systems (ADAS) and is moving towards autonomous driving. New technologies like high frequency communications, global positioning systems, radars, Bluetooth, Wi-Fi are today implemented in vehicles with extremely varied powertrain architectures. Depending on the vehicle model and brand, electrified vehicles may have one or two main electrical motors (with many other small ones used for specific functions) and high voltage battery/ies located in different parts of the vehicle (under the rear seats, under or along the floor of the vehicle). The resulting electromagnetic environment inside a vehicle is therefore extremely complex, dynamic and covering a broad range of frequencies, and thus very difficult to characterize [2].

The effects on health of electromagnetic fields have been studied for several decades and there is no clear evidence of possible long-term effects. On the contrary, physiological direct effects are well known. Direct effects occur above certain thresholds and consist of electrostimulation of nerves at low frequencies (1 Hz to 10 MHz) and heating of body tissues at higher frequencies (100 kHz-300 GHz). Indirect effects are also known and include: initiation of electro-explosive devices, electric shocks or burns due to contact currents, projectile risk from ferromagnetic objects, interference with medical devices, etc. Direct effects are linked to in-body quantities, not measurable in practice, that depend on the frequency: Current density J (mA/m^2) up to 10 MHz, specific energy absorption rate SAR (W/kg) for frequencies between 100kHz – 10 GHz, power density S(W/m^2) for frequencies between 10 GHz – 300 GHz. These in-body quantities are translated into measureable quantities by mathematical models and experimental investigations: E-field strength E (V/m), H-field strength H (A/m), B-field magnetic flux density B (μT), equivalent plane wave power density S_{eq} (W/m^2).

Adverse effects related to prolonged exposure to higher frequencies have been under discussion for some time due also to the mass adoption of mobile phones. Exposure to lower frequencies is not perceived as risky even if we are daily exposed to household appliances and generically to the power frequency of 50 Hz. However, the tendency to perceive the unknown as a threat, together with the role of vehicles in our everyday lives, leads to concerns about EV safety due to prolonged and close-proximity exposure to stray low frequency magnetic fields produced by electrical powertrain systems.

2.2 Definition of the problem

Electromagnetic fields generated by and inside electrified vehicles (electric EV and plug-in hybrid PHEV) are characterized by highly variable broad spectrum waveforms, being combinations of static and time-varying components. EVs, PHEVs, and charging devices generate these fields during operation (accelerations, regenerative braking, conductive or wireless charging, control communications). These operations result in different exposure situations for electric vehicle users (i.e. low frequency magnetic fields, radio transmissions at higher frequencies). Potential threats, such as possible interference with active implanted and wearable medical devices, may concern vehicle occupants, as well as passers-by and different users [3]. In electric/hybrid vehicles, low frequency magnetic fields are mainly produced by traction currents flowing in the high voltage power network, between batteries, inverters and engines (electrical or internal combustion engine) [4], [5], wheels, and other equipment such as the power steering pump. Currents involved during strong accelerations, regenerative braking, and fast charging can reach peaks of hundreds of Amperes, producing high magnetic fields. The subject of our study was the magnetic flux density B (μT) also called B – field, which is one of the measurable quantities that characterizes magnetic fields at low frequencies.

3 Background information

3.1 Relevant regulations and guidelines

In Europe, Council Recommendation 1999/519/EC [6] sets EMF reference levels (RLs) for the general public (Table 1). It is based on guidelines published in 1998 by the International Commission on Non-Ionizing Radiation Protection (ICNIRP) [7], which is the technical-scientific reference body for electromagnetic fields and optical radiation.

Table 1: Reference levels for general public exposure to time-varying magnetic fields up to 10 MHz varying with the frequency (f).

Frequency range	B field (µT)
Up to 1 Hz	4×10^4
1 – 8 Hz	$4 \times 10^4/f^2$
8 – 25 Hz	5000/f
0.025 kHz – 0.8 kHz	5/f
0.8 – 3 kHz	6.25
3 – 150 kHz	6.25
0.15 – 1 MHz	0.92/f
1 – 10 MHz	0.92/f

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In case of exposure to multiple frequency fields, these guidelines stipulate that the sum of the spectral content, calculated neglecting the phase of the waveforms, according to equation 1, be below the RLs:

$$\sum_{j=1Hz}^{10MHz} \frac{X_j}{AL(X_j)} \leq 1 \qquad (1)$$

Where X_j is the field strength at frequency j, $AL(X_j)$ is the field strength RL at frequency j.

In the presence of coherent waveforms this could lead to conservative results. For this reason, ICNIRP 2010 guidelines introduced the weighted peak method (WPM) [8] for non-sinusoidal multiple frequency fields then implemented into the Directive 2013/35/EU for workers' exposure [9]. This method weights the complex waveforms with a filter function as expressed in equation 2, taking into account the phase of the waveforms:

$$\left|\sum_i \frac{A_i}{EL_i} \cos(2\pi f_i t + \theta_i + \varphi_i)\right| \leq 1 \quad (2)$$

Where t is time , A_i is the amplitude of the ith harmonic component of the field, EL_i is the exposure limit at the ith harmonic frequency fi, and θ_i, φ_i are phase angles of the field and phase angles of the filter at the harmonic frequencies.

Depending on the source of possible field emissions, different international standards set the requirements and the measurement procedures. Table 2 shows some examples.

Table 2: Examples of international standards regarding electromagnetic fields exposure and their measurement.

Standard ID	Title
IEC 61786 -1: 2013	Measurement of DC magnetic, AC magnetic and AC electric fields from 1 Hz to 100 kHz with regard to exposure of human beings - Part 1: Requirements for measuring instruments
IEC 61786 -2: 2014	Measurement of DC magnetic, AC magnetic and AC electric fields from 1 Hz to 100 kHz with regard to exposure of human beings - Part 2: Basic standard for measurements
IEC 62110:2009 / Cor-1: 2015	Electric and magnetic field levels generated by AC power systems - Measurement procedures with regard to public exposure
IEC 62311: 2019	Assessment of electronic and electrical equipment related to human exposure restrictions for electromagnetic fields (0 Hz - 300 GHz)
IEC/TR 61000-2-7: 1998	Electromagnetic compatibility (EMC) - Part 2: Environment - Section 7: Low frequency magnetic fields in various environments
IEC 62233: 2005	Measurement methods for electromagnetic fields of household appliances and similar apparatus with regard to human exposure
IEC TS 62764 – 1:2019	Measurement procedures of magnetic field levels generated by electronic and electrical equipment in the automotive environment with respect to human exposure - Part 1: Low frequency magnetic fields

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Technical Committee 106[1] of the International Electro-technical Commission (IEC) is in charge of the definition of international standards on measurement and calculation methods to assess human exposure to electric, magnetic and electromagnetic fields. Amongst these standards, technical specification IEC TS 62764 ed.1 [10], published in September 2019, is specific for measurements of magnetic field levels generated by electronic and electrical equipment in the vehicle environment. It is worth clarifying that a technical specification (TS) has the same function as an international standard, with the advantage of reducing the time needed for publication. The engineering/science related to this topic is still evolving. There are still many open questions and therefore there is an urgent need for guidance in this area. Hence new information and experimental evidence gathered during the time between initial publication of the TS and its conversion into an international standard (IS) is valuable for refining measurement procedures and methodologies. The procedure includes the search for maximum values of B – field in the frequency domain in different volumes inside the vehicle during charging, driving, idle, acceleration and deceleration conditions with all the appliances turned on.

In the meanwhile, China and the United States have already issued their own recommended measurement test procedures for the assessment of in-vehicle magnetic fields. The Electric Transportation Applications of the Idaho National Laboratory, part of the Department of Energy of United States, developed the procedure ETA HTP 09 "Measurement and Evaluation of Magnetic Fields (EMF) and Electromagnetic Radiation (EMI) generated by Hybrid Electric Vehicles". This procedure foresees the determination of maximum, minimum and average values of magnetic field at various locations inside the vehicle during the SAE J1634 driving cycle and during a "three speed test" including different operational modes: acceleration, three different constant speeds (16/40/64 km/h), deceleration, charging.

China published its own procedure GB/T 37130-2018 "Measurement methods for electromagnetic fields of vehicle with regard to human exposure" at the end of December 2018, specifying the exact positions where to perform the measurement for vehicles, motorbikes and buses. Strict requirements for instruments in terms of frequency resolution are also set. Different test conditions are identified: charging, idling (static state) with the motor system in standby, the engine idle and all on-board appliances turned on (i.e. high beam headlights, air conditioning radio on, front wiper motor at maximum speed), driving with all appliances turned on (if hybrid also with the internal combustion engine working), doing maximum achievable accelerations and decelerations up to the maximum speed. The required measurement methods include time and frequency domain records of the magnetic field (max and actual values). Table 3 shows the main differences and similarities between these three procedures.

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[1] https://www.iec.ch/dyn/www/f?p=103:7:0::::FSP_ORG_ID,FSP_LANG_ID:1303,25

Table 3: Main differences and similarities between the measurement procedures of magnetic field levels inside vehicles.

	GB/T 37130-2018	IEC TS 62764 – 1:2019	ETA HTP 09
Measurement locations	Measuring positions specifications for Class M passenger car, L-type motorcycles, N-type commercial vehicle(truck) , M-class commercial vehicle (bus)	Measuring positions specifications only for M1 and N1 class	N.A.
Number of measurements per location	Different measurement points for each identified position	Single measurement point in a defined volume: no clear description	Single measurement point in a defined volume: no clear description
Measurement method	Time domain and frequency domain	Research of maximum; frequency domain	Time domain
Instrumentation	Strict instruments requirements in terms of frequency resolution	No instrument requirement in terms of frequency resolution	N.A.
Background	Same background requirements		N.A.
Vehicle set-up	Similar vehicle set up requirements (brightness of lights, front wiper motor speed, air conditioning, radio, state of charge - SoC)		N.A.
Operating conditions	Similar measurement phases (Stationary, Driving, Acceleration, Charging)		

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IEC TS 62764 ed.1 is very similar to GB/T 37130-2018. According to these procedures the vehicle should be tested in different operating conditions: stationary, driving, during acceleration and decelerations (±2.5 m/s^2 or more) and during charging, with vehicle electrical systems (lights, wipers, air conditioning, heating, etc) in their worst-case mode of operation. In both cases the background B - field intensity in the measurement site environment must be less than 10% of the reference values. Furthermore, both procedures allow measurements on a standard chassis dynamometer without requiring the use of an anechoic chamber.

According to IEC TS 62764 ed.1, the probe to be used for magnetic field measurements shall comply with the requirements of IEC 61786-1. These requirements are very similar to those of GB/T 37130-2018. In fact, the measuring instrument should be isotropic and its outer diameter should not exceed 13 cm. It should be able to perform measurements in time and frequency domains in the range 1- 400 kHz. However, in addition, GB/T 37130-2018 explicitly states strict specifications on the frequency resolution of the instrument (see Table 4), while IEC TS 62764 – 1:2019 has no requirements for frequency resolution.

Table 4: Frequency resolution requirements for instrumentation indicated in GB/T 37130-2018.

Frequency range	Resolution
10 Hz – 5 kHz	≤ 1 Hz
5 kHz – 50 kHz	≤ 5Hz
50 kHz – 400 kHz	≤ 50 Hz

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Measurement locations in IEC TS 62764 ed.1 are identified in terms of volumes representative of feet, legs, trunk and head positions applicable to categories M1 and N1. GB/T 37130-2018 provides instead a detailed description of measurement locations and exact positions where the probe should be placed for: Class M passenger cars; L-category motorcycles; N-type commercial vehicles (truck); and M-class commercial vehicles (buses). The measurement method described in IEC TS 62764 ed.1 requires a scan in the frequency domain within each volume, moving the probe slowly to determine the location of the maximum value of B-field. Once localized, a final frequency domain measurement is performed. According to GB/T 37130-2018, a spectrum should be acquired for each position, while in the time-domain WPM is applied with Max Hold function activated: The maximum value of B – field is retained over time, updating the value only if the a new greater value is found.

The ETA HTP 09 procedure has similar operating conditions with the addition of the SAE J1634 driving cycle. It requires that B - field values be acquired over time, and that the assessment in the frequency domain be performed in post processing.

3.2 Literature survey

Several test campaigns carried out in real world conditions using different instrumentation and different protocols have supported modelling and simulation activities in order to fully characterize the electromagnetic environment inside a vehicle. Authors in [11] measured the magnetic field inside 11 different vehicles (BEV, HEV, PHEV, FCEV, conventional ICE) up to 10 MHz, considering the magnetic field generated by different sources within the vehicle. In [12], [13], [14] different vehicles (gasoline, diesel, full and mild hybrids, electric) were tested in different conditions (idling, constant speed, on a test route with accelerations and decelerations). Magnetic field was recorded by means of different broad band meters with different settings placed in different locations inside the vehicle. In [15], a test campaign on 13 vehicles (9 electric or hybrid and 4 gasoline) focused on electric and magnetic field measurements in two different ranges of frequency (120 Hz to 10 kHz and 1.2 to 100 kHz). Authors of [16], [4] developed a simulation model for the evaluation of the magnetic fields emitted by the batteries and by the inverter in an EV, supported by laboratory measurements. In [17] a model considering a simple structure of a vehicle, the magnetic earth field and the magnetostatic field produced by traction currents, was validated by real measurements. Magnetic fields encountered on trains, buses and public transport have also been considered in [18],[19],[20] although generated magnetic fields are generally lower than international limits. Authors in [20] highlight that magnetic fields, intermittent fields with complex waveforms could have greater biological effects than electric and steady state fields. In [21] a 70 kW vehicle powertrain was tested in a laboratory under steady state conditions with different combinations of speeds and loads, focusing on cables and enclosure of the inverter and of the motor.

A European research project (EM_SAFETY) funded under the seventh framework programme aimed at evaluating safety of electric vehicles, recommending strategies for proper EV design and increasing public confidence in the safety of fully electric vehicles (FEV) as far as EMF are concerned. The study involved nine electric vehicles, which were compared with 3 internal combustion engine cars. This project was carried out in the period 2011-2014, when electric vehicle models were limited and not so heterogeneous and developed as the present. Several publications and reports concerning technical measurements and evaluations were published under this project, [11], [22]· [23], [24]. Considerations related to human health [25] based on in vitro experimental research [26] underline that magnetic fields do affect living systems, even if comprehension of the mechanisms by which they interact with a body's cells and human DNA has not been achieved. Authors in [26] affirm that static magnetic fields are not classifiable as carcinogenic to humans, and they do not support the view that ELF magnetic fields are possibly carcinogenic to humans. Hence, the overall finding of the project EM-SAFETY was that there are no risks for human health in electric vehicles [27].

Table 5 summarizes some details of the works described in these scientific publications. Used instrumentation, set up, operating conditions, test route, post processing and results are listed. Depending on the publication, technical details about setups and data processing are also available. In some cases the instrumentation used to measure the magnetic flux density (B – field) is the same. Operating conditions are similar for all measurements (idling, constant speeds, accelerations and decelerations on different test routes or in laboratory). Sensor positions varied inside the vehicle. Usually the probe was placed on each seat at different heights (foot, chest, head). Maximum or root mean square (RMS) values for B - field are recorded in time and/or in frequency domain, depending on the instrumentation, and then geometric mean and standard deviation are considered during post-processing. In some studies the WPM is used and the results are expressed in terms of ratio with the reference values (1998 or 2010 ICNIRP guidelines). Findings and results reveal that magnetic field levels depend on vehicle architecture and driver behavior. In general, B is higher in hybrid and electric vehicles than conventional (gasoline and diesel) ones and higher values of B – field are recorded at driver's foot level and at rear seats, mainly depending on the arrangement of the electric components and cabling between the battery and the engine [12],[13],[21],[22]. Moreover, higher fields were recorded in driving conditions at high speeds [11] and during regenerative braking and accelerations [14],[21]. During strong acceleration of the vehicle, indeed, the traction-battery current can reach levels close to 300 A generating a temporary magnetic field greater than 100 μT [16].

Table 5 Summary of the available literature about low frequency magnetic field emitted by electrified transports.

"Magnetic Field Exposure Assessment in Electric Vehicles" [11]				
Vehicles	*Operating conditions*	*Where*	*How*	*Instrumentation*
8 Evs 3 conventionals	low and high speed max accelerations max decelerations	Laboratory tests / Outside tests (area with restricted access straight road 0-60km/h; for few vehicles steep slope and high speed on highway, max accelerations and decelerations	Not specified	Low Frequency Fluxgate magnetometers: Bartington MAG-03 (0-3 kHz), Sensys FGM 3-D/100 (0-1.2 kHz) High Frequency Narda EHP 50D (5 Hz -100 kHz) Spectran NF-5035 (1 Hz-10 MHz) Current Sensor Fluke i310s (0-300 A, 0-20 kHz), Acceleration sensor ST Microelectronics LIS3LV02DL 6g, OROS analyzer OR36) Non magnetic mannequin
Instrumentation set up	*Measurement procedure*	*Sensor position*	*Data processing*	*Findings*
OR36 set up: low pass filter cut-off 2kHz, sampling frequency 5.12 kHz for LF sensors, HF sensor stand alone with own sampling and recording system.	Spectrograms, B – field spectra and time domain, identification of external perturbations	front passenger seat (sensors near head, seat and foot), LF sensor in the trunk close to the battery.	Weighted peak calculation (2010 ICNIRP guidelines)	Magnetic fields of: hundreds of μT at f< 1 Hz (traction currents), 0.1 up to 2 μT between few Hz and 1 kHz (wheels, regenerative breaking, steering pump, combustion engine), f> 1 kHz less than 100 nT (inverter).
"ELF magnetic fields in electric and gasoline-powered vehicles" [12]				
Vehicles	*Operating conditions*	*Where*	*How*	*Instrumentation*
6 gasoline-powered vehicles and 8different electric vehicles	Driving	16.3 km rectangular loop (elevation change 105 m, roadway climbs 8.5 km, highway 4.7 km)	Not specified	EMDEX Lite Broadband meters (40-1000 Hz)
Instrumentation set up	*Measurement procedure*	*Sensor position*	*Data processing*	*Findings*
Sampling every 4 sec	Each component of the magnetic field, and the resultant total	6 positions: driver floor, rear central floor, passenger seat, rear passengers' seats	Log transformed values of Geometric mean and standard deviation	Higher B - field in EVs compared to conventional vehicles. Higher values are recorded on the floor.
"Characterization of Extremely Low Frequency Magnetic Fields from Diesel , Gasoline and Hybrid Cars under Controlled Conditions" [13]				
Vehicles	*Operating conditions*	*Where*	*How*	*Instrumentation*

3 Diesel, 4 gasoline, 3 hybrids	STANDING condition: idling, 2500 rpm, DRIVING: constant speeds 40km/h, 80 km/h (2 repetitions)	segment of a straight road 1.3km little traffic low background MF	lights on, A/C radio off	EMDEX-II ELF MF meters
Instrumentation set up	*Measurement procedure*	*Sensor position*	*Data processing*	*Findings*
sampling rate 1.5s broadband mode (40-800Hz)	spot measurements (moving sensors to find the max) / continuous measurements (sensors at 4 passengers simultaneously near torso) 11503 observations BK twice a day	SPOT MEAS: in contact with the engine hood closed 4 seats, inside the trunk. CONTINOUS MEAS: sensors at 4 passengers simultaneously near torso	arithmetic and geometric means and standard deviation 5th 95 th	Higher magnetic (2 – 10 μT) at floor and driver's foot level and in the rear increasing with the speed and the accelerations. Average in the cars' seats 0.02 – 0.05 μT
"Testing hybrid technology cars: Static and extremely low-frequency magnetic field measurements" [14]				
Vehicles	*Vehicle operating conditions*	*Where*	*How*	*Instrumentation*
3 full hybrids, 3 mild hybrid	Idling, driving: 20-40 km/h, 80-120 km/h, over 120 km/h	Not specified	Not specified	Narda STS EFA 300 with isotropic probes Metrolab ETM-1
Instrumentation set up	*Measurement procedure*	*Sensor position*	*Data processing*	*Findings*
5 Hz – 32 kHz	Maximum value of the B – field (1998 ICNIRP guidelines)	12 positions: for 4 seats at 3 heights (feet, chest, head)	FFT 1Hz spectral resolution in the range 5 Hz – 2 kHz	Higher magnetic fields at rear seats at foot level during accelerations and braking. Variations with driver's behaviour and vehicle structure.
"Electric and Magnetic Fields < 100 kHz in Electric and Gasoline-powered Vehicles" [15]				
Vehicles	*Operating conditions*	*Where*	*How*	*Instrumentation*
4 gasoline, 3 EV and 6 Hybrids	driving accelerations decelerations, use of directional signals (up to 60mph 96.6km/h)	city roads highway	radio off	Narda EHP 50C EHP 50D
Instrumentation set up	*Measurement procedure*	*Sensor position*	*Data processing*	*Findings*
max hold two separated meas for repeatability span 10 or 100 kHz	1 bk floor rear seat EF between roof and seat	sensor moved inside the vehicle	Mean and standard deviation	Max measured electric field: 29.6 V/m, Max measured magnetic field: 18.7 μT 0-10kHz
"Passenger Exposure to Magnetic Fields due to the Batteries of an Electric Vehicle" [16]				
Devices Under Test	*Operating conditions*	*Where*	*How*	*Instrumentation*

single NiMH battery module	Battery modules connected to a dc-dc converter	Laboratory tests	Steady state currents	MF meters (F.W Bell 5170 dc; Combinova MFM10 for ac)
Instrumentation set up	*Measurement procedure*	*Sensor position*	*Data processing*	*Findings*
	B - field (0- 2 kHz) RMS 3 axis values.	Different distances from the battery and different working points. (20 cm in the Z+ direction worst case)	Offset background MF subtracted.	Currents up to 300 A produce a magnetic field up to 106 μT
"Evaluation of the magnetic field generated by the inverter of an electric vehicle" [4]				
Devices Under Test	*Operating conditions*	*Where*	*How*	*Instrumentation*
SEMIKRON SKS 60F B6CI 35 V12	(60 Arms, DC input voltage 650 V, output voltage 400 Vrms)	Laboratory tests	Not specified	MF meters (F.W Bell 5170 dc; Combinova MFM10 for ac)
Instrumentation set up	*Measurement procedure*	*Sensor position*	*Data processing*	*Findings*
	B - field (0- 2 kHz) RMS 3 axis values. Three measurements each current/distance combination.	5 distances from the inverter surface using two values of current (39 A and 58 A) in Y+ and Z+ directions.	Offset background MF subtracted. (2010 ICNIRP guidelines)	Max Magnetic fields in Y+ direction: ≈ 9 μT (current 39A), ≈ 12 μT (current 58A) at 10 cm distance.
"Forward model computation of magnetostatic fields inside electric vehicles" [17]				
Devices Under Test	*Operating conditions*	*Where*	*How*	*Instrumentation*
Three door EV (late '90s)	Not specified	Not specified	Not specified	Bartington MAG-03 (0-3 kHz), Narda (5Hz -100 kHz), Spectran (1Hz – 1 MHz)
Instrumentation set up	*Measurement procedure*	*Sensor position*	*Data processing*	*Findings*
Not specified	Not specified	Non-magnetic mannequin at passenger location (head, stomach, foot for low frequency, chest, seat, foot for high frequency), rear plate, rear battery	Not specified	Validation of a model for magnetostatic field
" Passenger Exposure to Magnetic Fields on go- Trains and on Buses, Streetcars, and Subways run by the Toronto Transit Commission, Toronto, CANADA" [18]				

Devices Under Test	*Operating conditions*	*Where*	*How*	*Instrumentation*
54 seats on 10 Buses, 65 seats on 10 streetcars, 54 seats of subways, 10 seats for 6 compartments of GO-trains	In motion during accelerations and decelerations	On road	Not specified	Omni – directional Trifield meter (0.2 (0.02 µT)– 3 mG (0.3 µT) resolution 0.2 mG (0.02 µT), 30 – 500 Hz)
Instrumentation set up	*Measurement procedure*	*Sensor position*	*Data processing*	*Findings*
Sampling rate every 5 or 10 sec	B – field	Chest height (80 – 100 cm above the floor)	Mean	Average magnetic fields: GO trains 2mG (0.2 µT), buses 11 mG (1.1 µT), streetcars 30 mG (3 µT), subways 30 mG (3 µT)
"Measurement and analysis of electromagnetic fields from trams, trains and hybrid cars" [19]				
Devices Under Test	*Operating conditions*	*Where*	*How*	*Instrumentation*
100 trains and trams , 1 hybrid vehicle	In motion accelerations and decelerations	Town	Not specified	EMDEX II (40 – 800 Hz) Narda EHP 50 (5-100 kHz)
Instrumentation set up	Measurement procedure	Sensor position	Data processing	Findings
Sampling rate 3 sec (EMDEX II) 30 sec EHP 50	Frequency spectrum	Floor, waist, seats levels	Not specified	Higher values on the left side and rear seats of hybrid vehicle. Magnetic field increases with accelerations. Max 35 mG (3.5 µT) (rear left floor), 87 mG (8.7 µT) (trains)
"Recommendations for mitigating low frequency magnetic field exposure in hybrid/electric vehicles" [21]				
Devices Under Test	*Operating conditions*	*Where*	*How*	*Instrumentation*
70 kW vehicle electrical powertrain	9 combinations of speeds and loads under steady state conditions	Laboratory test bed	Not specified	Narda ELT – 400
Instrumentation set up	*Measurement procedure*	*Sensor position*	*Data processing*	*Findings*
Not specified	Weighted peak?	Inverter enclosure, inverter cable entry, mid-point of motor cable, motor cable entry, motor enclosure	(1998 ICNIRP guidelines)	Ratios with the reference values (1998 ICNIRP guidelines) in percentage: inverter enclosure 26 – 65%, motor enclosure 50 – 440%, mid-point of cables 140-590%, inverter cables entry 200-1280%, motor cable entry 280-1420%.

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4 Scope of the study

The Joint Research Center started a research programme with two main objectives:

- To gather experimental data on low frequency magnetic fields generated by electrified vehicles
- To support the development of a standard test procedure in view of a possible future regulation for the type approval of electric vehicles.

JRC also established a collaboration with ENEA, the Italian Agency for New Technologies, Energy and Sustainable Economic Development aimed at the definition of a standard measurement procedure for the assessment of low frequency magnetic fields emitted by EVs and fast chargers. Two joint test campaigns took place during March and November 2019 involving two EVs and two High Power Charging Systems. Results about chargers are currently under publication.

4.1 Test facilities

JRC premises offer a unique testing capability of electrified vehicles with the possibility of using different facilities, including a semi-anechoic chamber.

Figure 1: VeLA 8 facility

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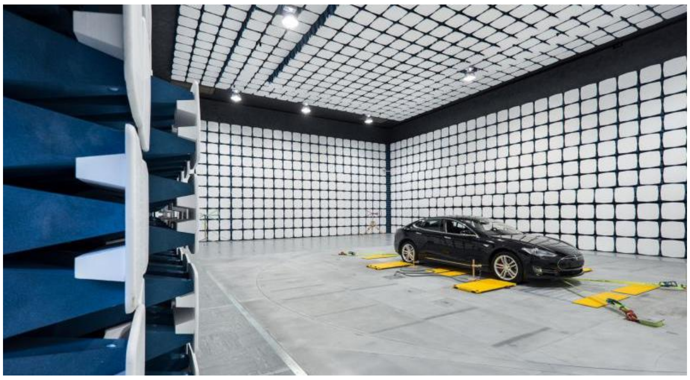
VeLA 8 is a climatic test chamber (-30 up to 50°C) designed to test full-electric and hybrid vehicles running on different fuels (gasoline, diesel, LPG, NG, hydrogen) and of different sizes (from passenger cars to vans). It is equipped with a 4 wheel driven (4WD) chassis dynamometer, with a customized emissions measurement system for hybrid vehicle testing which allows to properly sample the exhaust gas during the phases when the combustion engine is switched off, as well as with a system to acquire all the necessary electrical power measurements.

Figure 2: VeLA 9 facility



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VeLA 9 is a semi-anechoic chamber for electromagnetic compatibility testing of full-electric and hybrid vehicles of different sizes (passenger cars to little trucks). It comes with a four wheel driven (4WD) chassis dynamometer with a maximum speed of 210 km/h, a maximum acceleration and recuperative breaking of 10 m/s2. The chassis dynamometer is embedded within a turntable with a diameter of 11 meter that allows a 360 degree rotation of the vehicle under test, while running on the chassis dynamometer. This allows the characterization of electromagnetic emissions and the immunity of a vehicle or a charging system without needing to rotate the antennas and according the UNECE Regulation n.10 "Uniform provisions concerning the approval of vehicles with regard to electromagnetic compatibility".

4.2 What has been measured

The instrument used for the test campaigns described in this document is the EHP50G from Narda Safety Test Solutions, Cisano sul Nave (SV), Italy. It is equipped with an isotropic probe and allows measurements in both time and frequency domain within the range 1 Hz – 400 kHz with a declared resolution of 1 nT for the lower measurement range (0.3 nT ÷ 100 μT). The probe was properly calibrated at the time of the measurements. Its expanded uncertainty (coverage factor =2, confidence level 95%) includes linearity, anisotropy, frequency response, temperature, relative humidity, and the contribution of calibration uncertainty. It is declared to be between 3% and 5.3%, varying with the selected frequency and B – field range. However, a total expanded uncertainty of around 19% was calculated adding the contribution of the anisotropy measured by rotating the probe counter-clockwise in steps of 45° in a non-uniform field, which was found to be around 13%.

This instrument is designed to assess whether reference and action levels of 1999/519/EC and 2013/35/EU are exceeded, including also the option of WPM (according to RLs of 1998 and of 2010 ICNIRP guidelines [28]). However, WPM values are expressed as ratios of the RLs. B – field values measured in the time domain are not provided. The internal software of the probe graphically provides the frequency spectrum of the magnetic field in the selected frequency span displayed together with the selected RL curve, so that it is possible to verify whether RLs is exceeded. Simultaneously the software calculates if the measured B-field value satisfies equation 1. When weighted peak method is selected, the internal software provides the result of equation 2 expressed in percentage over time.

Being this study focused on low frequency magnetic fields emitted by electrified vehicles, the B – field was recorded in both time and frequency domains. In the time domain, WPM analysis was conducted considering RLs for general public exposure in the range 1 Hz - 400 kHz. In the frequency domain the measurements were performed in the restricted range from 25 Hz up to 2 kHz, which was considered a good compromise between the limited frequency resolution of the probe (shown in Table 6) and the range of interest for the measurements. In fact, larger frequency spans resulted in lower values due to the poor resolution.

Figure 3: Narda EHP50G Electric and magnetic field probe – analyser from 1 Hz up to 400 kHz.

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Table 6: Frequency resolution for each selectable frequency range of the probe EHP50G.

Frequency	Resolution
100 Hz	0.25 Hz
500 Hz	1.25 Hz
1kHz	2.5 Hz
2 kHz	5 Hz
10 kHz	25 Hz
100 kHz	250 Hz
400 kHz	1 kHz

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In some cases, additional measurements were executed by means of a magnetic DC and low frequency (up to 1 kHz) isotropic field probe-analyzer (Narda Safety Test Solutions HP01, Cisano sul Nave SV, Italy). It is made by three Hall effect elements, positioned orthogonal to each other and it allows customizable frequency span and measurement ranges.

Figure 4: Narda HP01 magnetometer field analyzer from DC up to 1000 Hz.

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Electrical parameters such as currents and voltages flowing through the battery and the electrical engine were recorded whenever possible by means of clamps and power analysers:

- Hioki clamps (0-500A) DC to 200kHz, ±0.3% accuracy with operating temperatures from -40°C up to 85°C.
- YOKOGAWA WT 1800, DEWEsoft SIRIUSi-CD

Figure 5: In-house instrumentation to measure and record electrical parameters.

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Table 7 includes the details of the used instrumentation.

Table 7: Details of the used instrumentation

Product Model	Serial Number	Calibration Dates
Narda EHP50G	100WY70264	19.12.2017 - 02.09.2019
Narda HP01	020WY71110	19.12.2017 - 04.09.2019
WT1806	91NA24055	11.06.2019
DEWEsoft SIRIUSi-CD	D017F30AE4- D017F30AE3	Bought in 2018

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Aiming at a full characterization of the magnetic field during vehicle operation, it would be useful to correlate the instantaneous acquired value of B - field with the exact value of currents flowing through cables inside the vehicle and with the vehicle's speed at that moment. This represents a big challenge in terms of measurement equipment. In the majority of cases it is extremely arduous to reach cables with current probes and it is even more complicated to acquire voltages from, for example, each phase of an electric engine. Parameters such as state of charge of the high voltage battery, currents involved during hard accelerations and regenerative breaking are needed to characterize the performance of the vehicle during its driving operations. A possible solution would be the recording of these parameters acquired via the ECU. However, each vehicle and in particular electric vehicles have their own protocol and encoding strategy for data communication and usually the time available for test campaigns does not allow reverse engineering of the communication protocol. For these reason, a specific acquisition software, currently under refinement, has been developed internally in order to design on one side customized driving cycles (with also a function of Driver Aid) and to simultaneously acquire, whenever feasible, several parameters: currents, voltages, powers from power analysers, speed, SoC, currents and all available data from ECU (via On Board Diagnostic - OBD) or by means of a dbc file when available) together with B - field from different probes. The software was able to acquire both analogue signals (such as the signal from the chassis dynamometer) and the speed signal via the control unit of the vehicle and to display them on a screen. Vehicle's speed was needed in order to allow the driver to follow and repeat customized driving cycles and it was available either from the chassis dyno software or via the Engine Control Unit (ECU) of the vehicle. However, in case of speed acquired from the control unit of the vehicle, a small delay in the visualisation had to be accepted.

4.3 Experimental fleet

Starting from mid-2018 different kind of vehicles were tested in our test facilities allowing our staff to gather experience about this specific topic:

- 2 different samples of L-category (L6e-BP)s vehicles of the same model and manufacturer (Aixam)
- 2 Plug-in Hybrid Vehicles (Mitsubishi Outlander, Hyundai Ioniq)
- 5 EVs (Renault Kangoo small, Nissan Leaf, Hyundai Ioniq, Volkswagen e-Golf, Jaguar I-pace)

Some of these vehicles were rented for the test campaign and usually were almost brand new and with a very low mileage,

The tested vehicles, in the majority of the cases, represent a single sample of each model and therefore the results cannot be fully generalized to other vehicles of the same model. However this should not be considered a significant limitation of the study, since this was intended as an exploratory research programme mainly focused on the methodology and not on the compliance verification with specific regulatory requirements.

Table 8: EVs tested at the Interoperability Centre during 2018 – 2019.

Dates	Vehicles	Max Delivered Power during charging	Battery Capacity	Engine Power
07/2018	Nissan Leaf	50 kW	24 kWh	80 hp (109 kW)
10/2018	VW e-Up	40 kW	18.7 kWh	82 hp (60 kW)
12/2018	Hyundai Ioniq	70 kW	38.3 kWh	88 (kW)
03/2019	VW e-Golf[2]	50 kW	35.8 kWh	136 Hp (100 kW)
11/2019	Jaguar I-Pace [3]	83 kW	90 kWh	400 Hp (294 kW)

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Vehicles in Table 8 were tested according to a protocol that evolved over time with experience. Therefore instrumentation settings, sensor positioning, and vehicle's operations during the measurements were modified with the final objective of improving reproducibility and robustness of the test procedure.

4.4 Test protocol

For the magnetic field measurement different locations were identified inside the vehicle approximately corresponding to the position of the head, body and feet of driver and passengers. Figure 6 shows the measurement locations identified by acronyms used to indicate each position and fully explained in Table 9.

Figure 6: Identification of the measurement locations inside the vehicle.

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[2] Tested in collaboration with ENEA

[3] Tested in collaboration with ENEA

Table 9: Acronyms of Figure 6 and their related locations.

Acronym	Location
FFL	Front Feet Left
FFR	Front Feet Right
FTC	Front Thorax Central
FTL	Front Thorax Left
FTC2	Front Thorax Left 2
FTR	Front Thorax Right
FHR	Front Head Right
FHL	Front Head Left
RFC	Rear Feet Central
RTL	Rear Thorax Left
RTC	Rear Thorax Central
RTR	Rear Thorax Right
RHL	Rear Head Left
RHC	Rear Head Central
RHR	Rear Head Right
RFL	Rear Feet Left
RFR	Rear Feet Right

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To carry out a complete characterization of the magnetic field inside the vehicle in the different operating conditions, the probe had to be moved from one measurement location to another. To assure repeatability, each measurement location was marked (with adhesive tape) to locate the probe rapidly and precisely and the probe was positioned keeping the same axis direction when repeating the test. Due to the limited frequency resolution of the probe EHP50G and due to the nature of the spectra with higher spectral content at low frequencies, the chosen span for the measurements was 25 Hz - 2 kHz with a frequency resolution of 5 Hz, as mentioned in the section 3.2.

As already mentioned, the experimental setup varied depending on the available instrumentation and the development status of the acquisition software developed ad hoc for the test campaign. The driving cycle included three different speeds with different accelerations and decelerations with the objective of reaching the maximum acceleration/deceleration and speeds of the vehicle. Each cycle was repeated several times to carry out the measurements in the time and frequency domain for each location. The measurements in the time domain were based on the WPM and the results were directly delivered by the instrument firmware in percentage. Results above 100% do not satisfy equation 2 and are considered above RLs. Concerning the frequency domain, one spectrum each 1.36 second was acquired using the instrument function "Autosave". This means up to one hundred spectra acquisitions for one single driving cycle. Data were analysed in terms of maximum wideband values of B – field and maximum value of weighted peak in order to identify the worst locations within the vehicle in terms of magnetic field value and potential exposure. Whenever possible, a correlation with speed, current and vehicle operation at that moment was derived. All the instrumentation was synchronized at the moment of the measurement. The chassis dynos settings were adjusted on the basis of the officially declared road loads as foreseen by WLTP (World-wide Harmonized Light-Duty Test Procedure) or with road loads based on NEDC (New European Drive Cycle).

5 Results and discussion

Results are expressed in the frequency domain as wideband B – field values in the frequency range 25 Hz – 2 kHz and in the time domain as WPM percentages.

5.1 Aixam

Two different L-category (L6e-BP) vehicles of the same model and manufacturer were tested. The 2-passenger mini-cars are part of JRC internal vehicles' fleets and are fully electric.

Figure 7: Aixam vehicle mounted on VeLA 9 roller benches

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The driving cycle used included a hard acceleration up to the maximum achievable speed (around 50 km/h), about 30 seconds at constant speed and a hard braking. The total estimated driving cycle duration was 1.2 minutes, as can be seen in Figure 8 that shows the current of one phase of the electrical engine and the battery current.

Figure 8: Currents of one phase of the electrical engine and of the battery

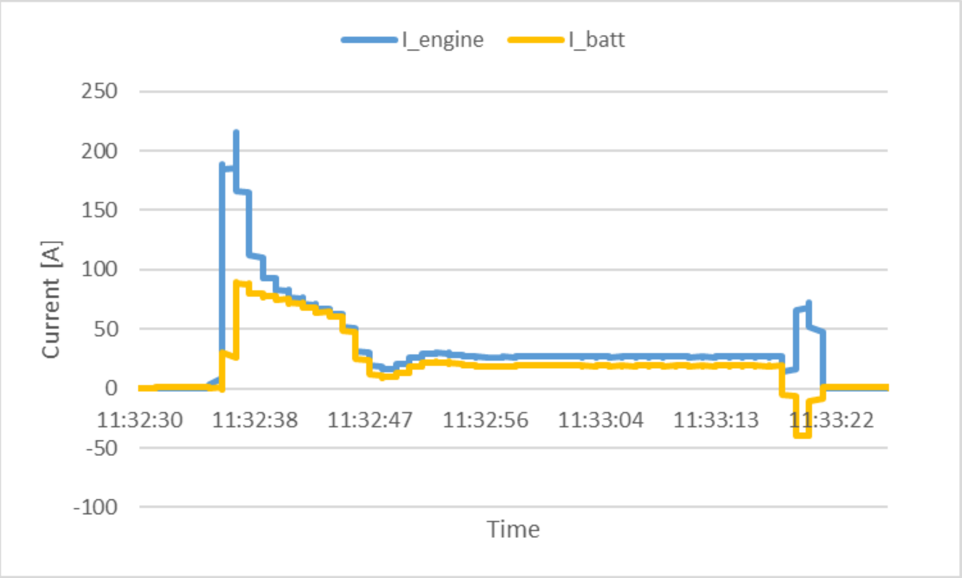

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Table 10 shows maximum values of B – field and percentage obtained with WPM during the driving cycle for both vehicles.

Table 10: Magnetic flux density B – field values (25 Hz – 2 kHz) and WPM percentages recorded in different locations inside the two Aixam vehicles.

	Vehicle 1		**Vehicle 2**	
Location	**B(μT)**	**WP (%)**	**B(μT)**	**WP (%)**
FFL	0.209	13.92	0.496	10.33
FFR	0.280	27.17	0.309	10.74
FTC	0.583	28.83	0.719	34.24
FTL	0.146	6.11	0.073	4.52
FTC2	0.246	19.43	0.146	9.78
FTR	0.106	18.76	0.106	8.35
FHR	0.466	11.32	0.084	7.63
FHL	0.250	3.82	0.055	15.99
RFC	0.188	22.07	0.061	3.94
RFL	0.140	1.6	0.046	1.63
RFR	1.640	1.85	0.982	8.47
Engine	15.467	13.93	18.074	-

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5.2 PHEV Hyundai Ioniq

In this case, the driving cycle used included a hard acceleration up to 120 km/h, about 30 seconds at constant speed and a hard braking (70 sec circa). In Figure 9 the current related to the high voltage battery during the driving cycle is plotted. Different scenarios and different locations were considered, such as two different states of charge (Full, less than 50%), engine switched on, gearshift, maximum acceleration. The probe was used with the option max Hold active during the driving cycle. This means that, during the cycle, the maximum value of B – field was retained for each frequency and it was updated only if a new greater value was acquired.

Figure 9: PHEV Hyundai Ioniq, High voltage battery current during the driving cycle (Ampere vs Seconds).

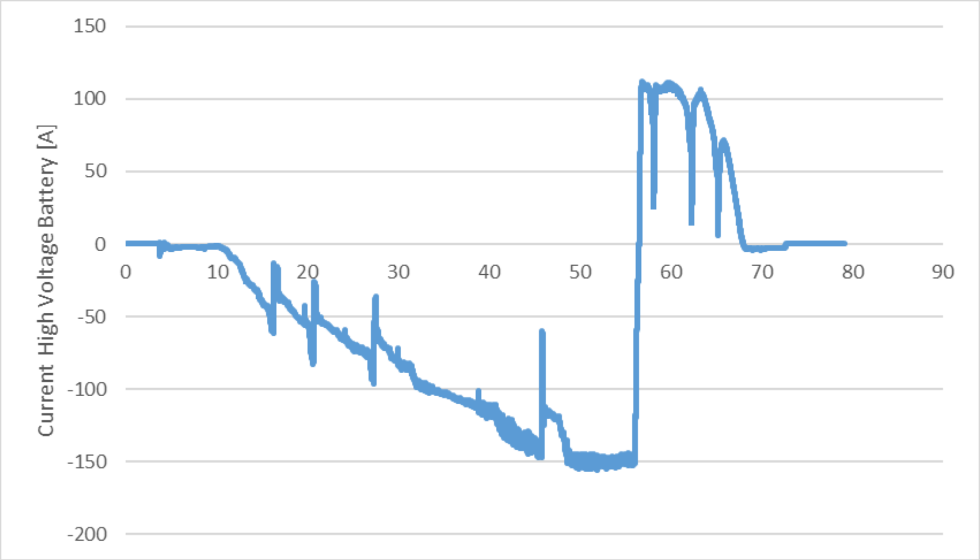

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Table 11: Magnetic flux density B - field values (25 Hz – 2 kHz) and peaks, frequency of the peak and WPM percentages recorded in different locations inside the vehicle.

Location	B(μT)	WP (%)	Specific conditions
FFL	1.828	101.90	Less than 50% of SoC
FFL	2.918	109.25	Full Charge
FFL	3.831	132.69	Full Charge, max acceleration
FHL	0.261	32.72	Engine switched on
FHL	0.268	-	Gearshift
FHL	1.455	38.59	Full charge
FFR	1.908	134.38	Less than 50% of SoC
FFR	1.656	184.4	Full charge
RFR	4.081	181.33	Less than 50% of SoC
RFR	3.135	-	Full charge

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Table 11 shows values of B – field and WPM percentages recorded in different locations inside the vehicle. Even if wideband values don't exceed 4 μT, results obtained with the WPM show peaks above 100%.

5.3 PHEV Mitsubishi Outlander

The Mitsubishi Outlander was tested in two different facilities (VeLA 8 and VeLA 9) to estimate the influence of the background B-field on the measurements. VeLA 9 is a semi-anechoic chamber certified to test electromagnetic emissions generated by vehicles as well as their immunity against interferences between 30 MHz - 18 GHz. For this reason, equipment typical of vehicle emission facilities (Driver Aid and other data acquisition systems) are not installed inside this chamber. Furthermore, this chamber is specifically design to test vehicles' electromagnetic compatibility and it is equipped with a shielded chassis dynamometer. VeLA 8 is instead a standard vehicle emission test facility without any measure to reduce the background EMF.

The background magnetic field was measured first with the chassis dynamometer turned on and with the vehicle off and then with the vehicle turned on.

The measurements inside the vehicle were carried out while driving the vehicle following a specific driving cycle that was repeated in the two test facilities VeLA 8 and VeLA 9. This was facilitated by the use a portable driver aid installed on a (laptop?) PC operating from its battery and placed outside the vehicle.

In the first case parameters such as speed, rpm, currents and voltages were acquired simultaneously by means of the laboratory acquisition system. Regarding the tests carried out in VeLA 9, the portable driver aid acquired the speed directly from the ECU of the vehicle with a small delay in displaying it on the screen.

Figure 10: PHEV Mitsubishi Outlander mounted inside VeLA 9 with its exhaust extraction system

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Figure 11: Mitsubishi Outlander, driving cycle and currents of front and rear engines.

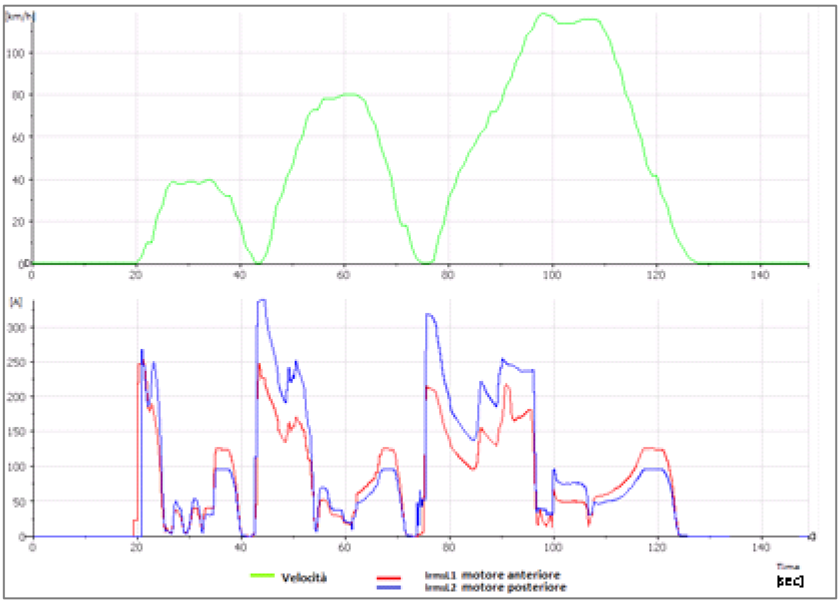

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Table 12 shows B – field values and the WPM percentages recorded in different locations inside the vehicle in VeLA 8 and VeLA 9 following the driving cycle of Figure 11.

Table 12: Magnetic flux density B – field values (25 Hz – 2 kHz) and WPM percentages recorded in different locations inside the vehicle in VeLA 8 and VeLA 9 laboratories following the same driving cycle.

	B(μT)		**WP (%)**	
Location	**VeLA 8**	**VeLA 9**	**VeLA 8**	**VeLA 9**
FFL	0.625	1.073	7.16	8.5
FFR	0.527	0.898	**160.33**	**150.57**
FTC	1.372	1.609	**521.25**	**360.4**
FTL	0.458	0.464	4.63	**118.19**
FTC2	0.392	0.324	**105.87**	**112.7**
FTR	0.672	0.449	**226.43**	**224.83**
FHR	0.202	0.220	3.1	55.83
FHL	0.340	0.331	**122.46**	**125.03**
RFC	0.840	0.793	**171.45**	**175.33**
RTL	0.844	0.810	5.51	**192.29**
RTC	2.111	1.867	**159.41**	**173.34**
RTR	3.817	3.473	**377.86**	**417.41**
RHL	0.677	0.775	3.59	79.98
RHC	0.934	1.097	**115.97**	**120.82**
RHR	2.232	2.302	**216.66**	**198.29**
RFL	0.682	0.794	6.12	**213.26**
RFR	0.948	1.310	**379.08**	**379.27**

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WP values displayed in bold exceed the RLs for general public exposure with peaks up to 379%. The occurrence of the WP peaks has been analysed but the peaks didn't appear at the same time even though the driving cycle was the same in all the measurements.

Table ***13*** shows the comparison between the measurements executed in the two different facilities (VeLA 8 and VeLA 9). Background values of B – field with the vehicle switched off and with the key turned on but the engine idle are respectively 0.006 μT and 0.024 μT for VeLA 9, 0.041 μT and 0.047 μT within VeLA 8. The contribution of the electrical equipment to the VeLA 8 background doesn't allow a distinction between the two conditions of vehicle on and off, which is instead possible considering VeLA 9 measurements. Furthermore, it should be underlined that these values refer to the chassis dynamometer turned on but at zero speed. Hence, these values are not representative of the dynamometer contribution during driving. However, even though there is a visible, albeit low, difference between background values obtained with a shielded chassis dynamometer (VeLA 9, Car Off) and VeLA 8, the worst case location coincides for background measurements and for B - field measurements in driving conditions (3.817 μT for VeLA 8 and 3.473 μT for VeLA 9). The location corresponds to the rear right passenger's seat (RTR). WP values displayed in bold exceed the RLs for general public exposure with peaks up to 379%. The occurrence of the WP peaks has been analysed but the peaks didn't appear at the same time even though the driving cycle was the same in all the measurements.

Table 13: Worst case location B – field background inside VeLA 8 and VeLA 9 with the vehicle off and on, B - field values and WP percentages measured during driving.

Worst Case Positon		**B(μT)**			
		VeLA 8		**VeLA 9**	
RTR	**Background**	**CAR OFF**	**CAR ON**	**CAR OFF**	**CAR ON**
		0.041	0.047	0.006	0.024
	Driving	3.817		3.473	
		WPM (%)			
		377.86		417.41	

JRC, 2020

5.4 EV Hyundai Ioniq

Background measurements revealed values below 0.028 μT with the vehicle off, 0.080 μT with the vehicle turned on. B – field was measured during DC fast charging and in driving conditions.

Figure 12: EV Hyundai Ioniq within VeLA 9.

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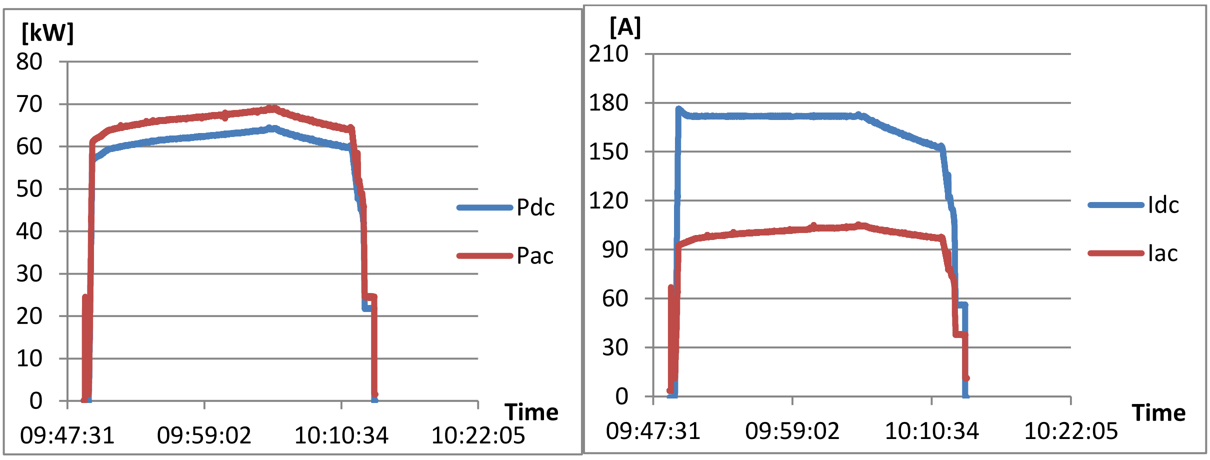
Charging conditions

Hyundai Ioniq was recharged at its maximum capability of 70 kW with one of the High Power Charger Systems (HPCSs) available at the Interoperability Centre. Measurements regarding the charger are pending publication. The charging process was monitored and recorded by the Yokogawa WT1800 power analyser. **Figure 13** shows charging powers and currents related to AC and DC side during a 70kW recharge.

Figure 13: Powers and Currents during Hyundai Ioniq Fast Charging



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B – field actual values were measured for each location indicated in Figure 6. The instruments (WT1800 and Narda EHP50G, HP01) were synchronized at the start of the test cycle.

Table 14: B - field values measured with the probe EHP50G within the frequency range 25 Hz – 2 kHz and B-field measured with HP01 within the range 0 - 1Hz during the recharge at full load.

	EHP50G	**HP01**
	B(μT) 25 Hz – 2 kHz	**B(mT) DC- 1 Hz**
FFL	0.074	0.063
FFR	0.033	0.052
FTC	0.129	0.079
FTL	0.0845	0.077
FTC2	0.062	0.038
FTR	0.055	0.075
FHR	0.047	0.047
FHL	0.037	0.030
RFC	0.086	0.105
RTL	0.094	0.046
RTC	0.073	0.069
RTR	0.043	0.072
RHL	0.082	0.058
RHC	0.039	0.071
RHR	0.028	0.078
RFL	0.187	0.172
RFR	0.0867	0.157

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B - field values reported in Table 14 are very low, considering that the maximum reached is 0.19 μT within the frequency range (25 Hz – 2 kHz). These values are of course consistent with the fact that fast charging involves direct currents. Static field monitoring was possible by means of the HP01 probe. Highest B - field value for DC – 1 Hz was 0.172 mT, whereas RL for static magnetic field within the Recommendation 1999/519/EC for general public exposure is 40 mT. The worst location was the same (rear feet left) for both instruments and frequency ranges.

Driving conditions

This vehicle has three selectable driving modes (Normal, Eco and Sport), three levels of coasting energy regeneration and two air conditioning modes (Normal and Eco).

The B-field values were recorded with the vehicle in its standard conditions and default settings (see Table 15). The SoC of the battery during the measurements was within the range 77-53%. The speed was recorded by means of the chassis dynamometer software, as shown in **Figure 14** The driving cycle, repeated for each location, included accelerations, decelerations, and constant phases at three different speeds (50/90/130 km/h), for a total duration of circa 3 minutes.

Figure 14: Driving Cycle speed recorded by the chassis dynamometer.

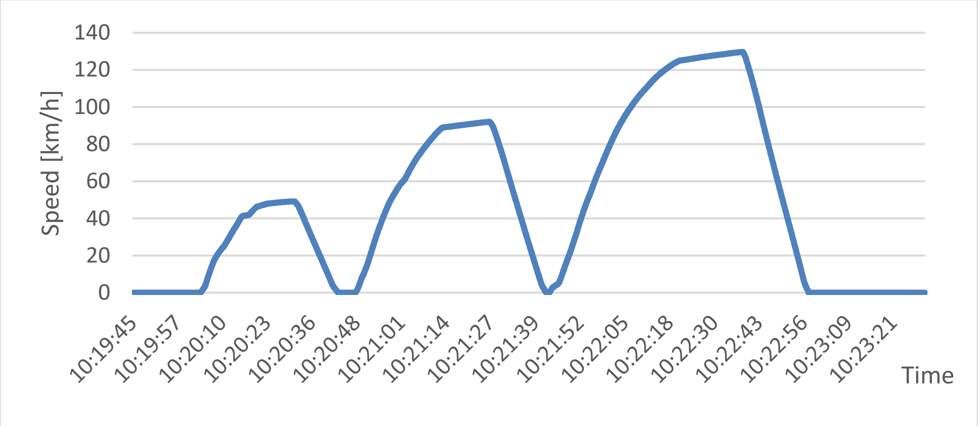

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Table 15 shows B – field values and WPM percentages measured inside the vehicle according to Figure 6.

Table 15: B – field values and WPM percentages recorded in different locations inside the vehicle.

Location	**B(μT)**	**WP (%)**
FFL	0.240	18.94
FFR	0.267	8.53
FTC	0.563	10.33
FTL	0.136	4.89
FTC2	0.119	4.19
FTR	0.146	2.3
FHR	0.081	2.11
FHL	0.049	4.17
RFC	0.214	3.71
RTL	0.224	8.6
RTC	0.138	2.25
RTR	0.307	2.76
RHL	0.085	54.9
RHC	0.081	2.12
RHR	0.043	1.66
RFL	0.248	14.11
RFR	0.786	6.26

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B – field recorded values were very low during driving. The higher B - field value was found at the location RFR (0.79 μT), while higher WPM percentages were recorded on the left side (locations FFL and RFL) and in the front compartment (locations FFR and FTC). Once the worst case locations have been identified, further measurements were performed using different combinations of available settings, according to Table 16, focusing on the front compartment (locations FFL and FFR)**.** Table 17 shows the results of this analysis. B – field values were similar to the ones measured with standard settings, while WPM percentages were higher reaching peaks above 100% in location FFR for cases c and f, both with the higher level of coasting energy regeneration. Measurements were repeated measuring WPM values of 11% circa.

Table 16: Different combinations of available settings used to characterize the worst case locations.

	Standard	**a**	**b**	**c**	**d**	**e**	**F**
Drive Mode	Normal	Normal	Normal	Normal	Eco	Sport	Sport
Climate Control	Normal	Eco	Normal	Normal	Normal	Normal	Normal
Coasting energy regeneration	Level 1	Level 1	Level 2	Level 3	Level 1	Level 1	Level 3

JRC, 2020

Table 17: B – field values and WPM percentages recorded in worst case locations with different combination of vehicle available settings.

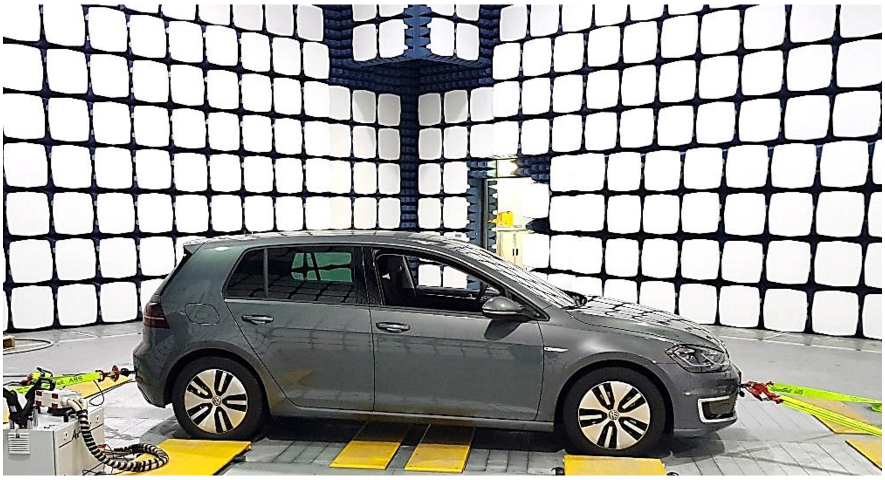
Settings			**B(μT)**	**WP (%)**
a		FFL	0.1946	26.08
		FFR	0.4351	26.57
b		FFL	0.244	19.23
		FFR	0.3888	112.85
c		FFL	0.2887	19.17
		FFR	0.5089	201.48
d		FFL	0.2786	24.7
		FFR	0.4581	9.71
e		FFL	0.2094	24.28
		FFR	0.4669	9.99
f		FFL	0.2708	23.85
		FFR	0.4782	120.82

JRC, 2020

5.5 EV Volkswagen E - Golf

Figure 15 shows the EV VW e-Golf installed on the chassis dynamometer inside VeLA 9 chamber.

Figure 15: VW E – Golf fixed inside VeLA 9.



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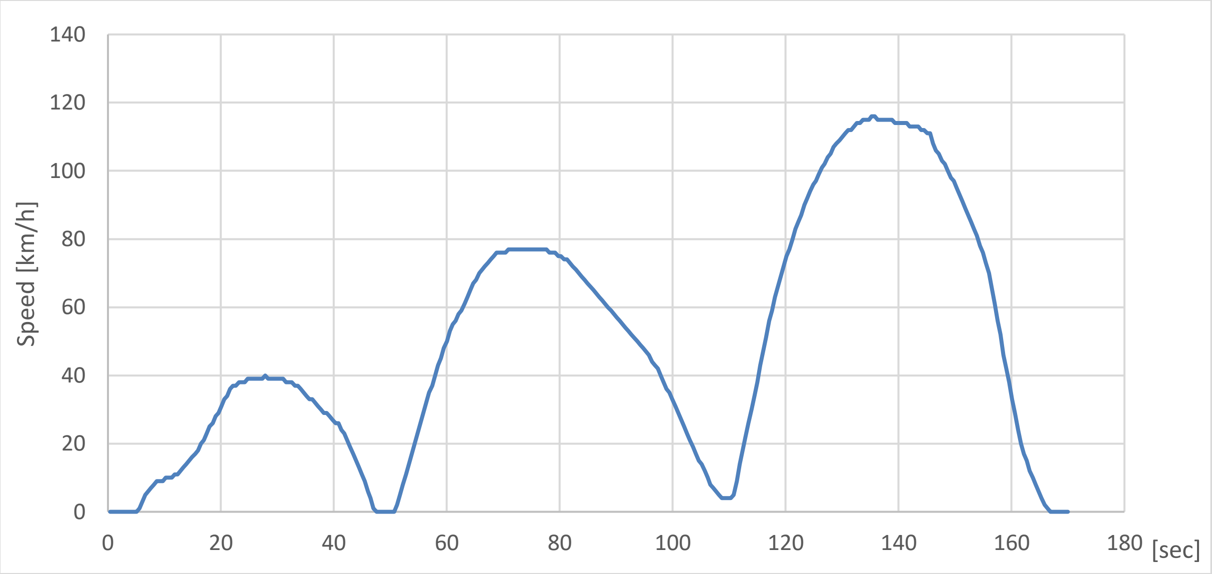
Electrical parameters such as state of charge, currents, voltages, vehicle speed were acquired via ECU and with power analyzers. Figure 16 shows an example of driving cycle recorded from the ECU of the vehicle. The signal was transferred to a screen by means of the internally developed software so that the driver was able to follow a precise pattern. However a small visualisation delay had to be accepted. The driving cycle included three different accelerations/decelerations and constant speeds patterns (0-40 km/h in 15 sec acc=0.74 m/s^2; 0-80 km/h in 15 sec acc=1.48 m/s^2; 0-120 km/h 15 sec acc=2.22m/s^2 for a total duration of 130 seconds).

Figure 16: Driving Cycle speed recorded from ECU.



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B-field was measured at the locations identified in the test protocol and using the same driving cycle. The results, presented in Table 18, reveal very low values of B-field and low percentages of WPM. The higher B - field value were recorded in correspondence of the rear passenger thorax (driver side), while the worst case location for WPM was at the front passenger foot (Table 19). B – field can easily vary due to small changes of boundary conditions (such as a deviation of the location of the probe or of the driving cycle, etc).

Table 18: Magnetic flux density B – field values (25 Hz – 2 kHz) and WPM percentages recorded in different locations inside the vehicle following the same driving cycle.

Location	B(μT)	WP (%)
FFL	2.552	8.36
FFR	1.104	12.21
FTC	0.420	5.18
FTL	0.399	2.25
FTC2	0.356	2.51
FTR	0.482	2.74
FHL	0.375	0.75
FHR	0.426	0.42
RFC	0.660	6.84
RTL	3.743	7.13
RTR	2.234	3.51
RTC	0.872	2.64
RHL	1.044	1.30
RHR	1.232	1.27
RHC	0.661	0.68
RFL	0.918	16.90
RFR	1.082	4.85
Trunk right	2.389	2.77
Trunk left	2.536	2.95

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Table 19: Maximum values of B –field in the frequency domain (25 – 2 kHz) and in the time domain with WPM.

	Worst Case Positon	
B(μT)	RTL	3.743
WPM (%)	RFL	16.9

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5.6 Jaguar I-Pace

Figure 17: Jaguar I Pace within VeLA 9

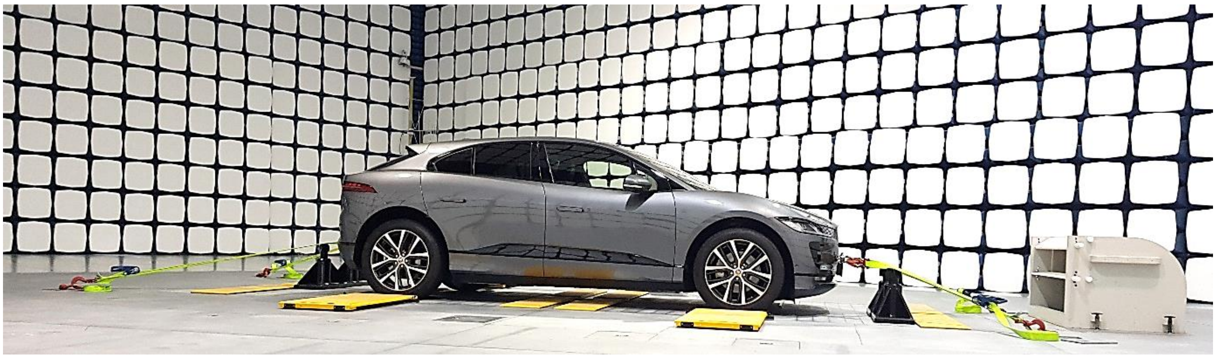

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Figure 17 shows the EV Jaguar in VeLA 9. The EV was chosen due to its power capabilities that allowed high power charging up to 83 kW. B – field was measured during DC fast charging and in driving conditions. Background values were below 0.027 μT with the vehicle off. Current and voltage of the high voltage battery as well as currents from one phase from both front and rear electric engines were recorded by means of power analyser.

Charging conditions

Jaguar I-Pace was recharged at its maximum capability of 83 kW with one of the High Power Charger Systems (HPCSs) available at the Interoperability Centre. Measurements regarding the values of the B-field generated by the charger are pending publication. The charging process was monitored and recorded by means of the power analyser DEWEsoft Sirius-PWR-MCTS2. B – field actual values were measured for each location indicated in Figure 6. ***Figure 18*** shows charging powers and currents related to the AC and DC side during a recharge up to 83 kW circa.

Figure 18: Powers and Currents during Jaguar I Pace Fast Charging.

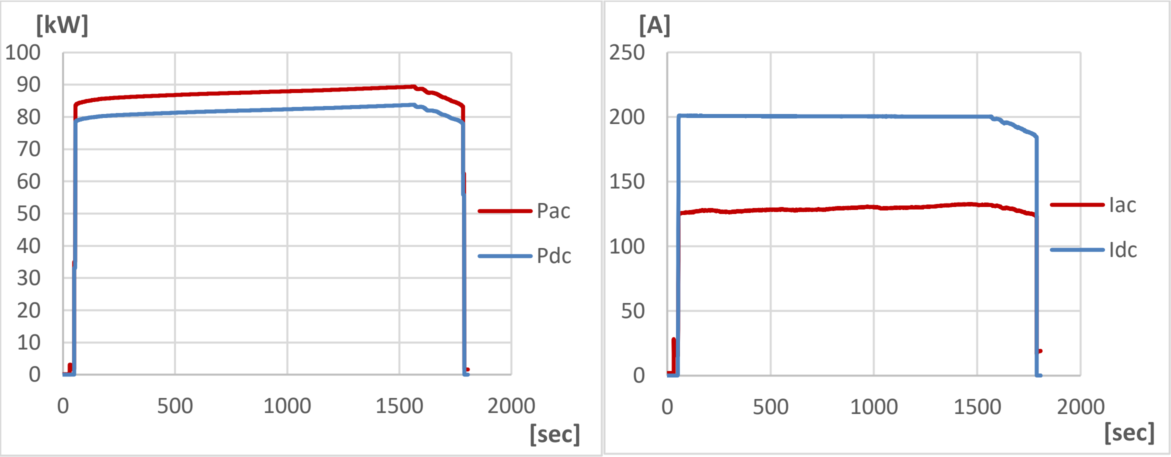

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Table 20 reports B - field wide-band values, exposure indices and WPM percentages measured during the recharge at full load (up to 83 kW). WPM percentages are below 1.5% in all locations within the vehicle. Hence, magnetic fields within the frequency range 2 – 2 kHz are far below the RLs during a DC recharge at up to 83 kW.

Table 20: B - field values, exposure indices and WPM percentages measured during the recharge at full load (up to 83 kW).

Location	B(μT)	WP(%)
FFL	0.371	1.48
FFR	0.271	1.19
FTC	0.197	1.34
FTL	0.027	1.17
FTC2	0.011	1.17
FTR	0.026	1.19
FHR	0.013	1.16
FHL	0.012	1.16
RFC	0.221	1.26
RTL	N.A.	1.18
RTC	0.129	1.21
RTR	0.112	1.18
RHL	0.019	1.19
RHC	0.011	1.14
RHR	0.011	1.16
RFL	0.612	1.58
RFR	0.422	1.48

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Driving conditions

The driving cycle was the same used for the Volkswagen e-Golf with three different accelerations/decelerations and constant speeds phases (0-40 km/h in 15 sec, acc=0.74 m/s2; 0-80 km/h in 15 sec, acc=1.48 m/s2; 0-120 km/h 15 sec, acc=2.22m/s2 for a total duration of 130 seconds). The speed, that was plotted on the screen for assisting the driver and then recorded, was taken from the chassis dynamometer and transferred within the chamber by means of coaxial cables. By means of the JRC internal acquisition software, it was possible to synchronize the electrical parameters with vehicle speed from the chassis dynamometer.

Table 21 shows B – field values and the percentages according to equation 1, recorded in the different locations inside the vehicle, are displayed. Maximum B – field values were recorded in the trunk reaching circa 2 μT. Percentages according to equation 1 were, in the majority of locations, below 15%. Maximum values of B-field don't always correspond to maximum equation 1 percentages during the driving cycle.

Table 21: B – field values and percentages (according to equation 1) recorded in different locations inside the vehicle following the same driving cycle.

Location	B(μT)	Equation 1 (%)
FFL	0.492	6.11
FFR	0.588	5.06
FTC	0.767	4.2
FTL	0.215	1.66
FTC2	2.922	7.75
FTR	0.327	2.85
FHL	0.139	0.67
FHR	1.387	2.59
RFC	0.869	9.17
RTL	0.987	2.52
RTR	1.531	11.87
RTC	0.66	2.92
RHL	0.669	1.42
RHR	0.7	2.89
RHC	0.549	1.84
RFL	0.399	3.07
RFR	0.715	8.47
Trunk right	2.178	14.98
Trunk left	2.951	4.6

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Table 22 show WPM percentages recorded during the driving cycle. The average values do not exceed 30%, while peaks in the trunk are above 70% for both probes.

Table 22: WPM percentages recorded in different locations inside the vehicle: averages and peak values during the driving cycle.

	WP (%)	
Location	**Average**	**Peak**
FFL	4.79	23.68
FFR	14.98	53.88
FTC	6.26	12.64
FTL	4.83	8.59
FTC2	5.31	8.32
FTR	6.38	12.52
FHL	3.53	6.72
FHR	4.09	7.3
RFC	13.37	38.21
RTL	26.35	44.04
RTR	30.13	48.6
RTC	13.63	24.47
RHL	9.96	16.98
RHR	11.04	19.9
RHC	1.79	2.97
RFL	9.57	24.75
RFR	13.38	33.67
Trunk right	34.91	76.96
Trunk left	2.37	4.23

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6 Conclusions

This study was carried out with the following objectives:

- To provide a clear picture of the state-of-the-art of the knowledge in this field by means of a comprehensive literature survey.
- To gather experimental data on low frequency magnetic fields generated by electrified vehicles of the latest generation by means of ad-hoc experimental campaigns carried out in the JRC's VELA laboratory.
- To support the development of a standard test procedure in anticipation of future electric vehicle type approval regulations.

In total nine different electrified passenger cars, including both pure electric vehicles and hybrids, were tested at the JRC's VELA facilities. The main focus was the assessment of the magnetic flux density (B-field), both in the time and frequency domain, inside the vehicle during various operating conditions.

The instrument used throughout the campaign follows the guidelines set in the standard IEC 61786-1:2013 "Measurement of DC Magnetic, AC Magnetic and AC Electric Fields from 1 Hz to 100 kHz with Regard to Exposure of Human Beings – Part 1: Requirements for measuring instruments" as suggested in IEC TS 62764 ed.1.

The results obtained in the experimental campaigns described in this report reveal that in general B – field values measured within PHEVs and EVs are far below the RLs indicated for general public exposure. Higher B-field values in the frequency range 25 Hz – 2 kHz were recorded in locations corresponding to feet positions and during hard accelerations and braking

The highest peaks of currents in the cables were recorded during strong accelerations and hard breaking rather than during constant speed phases. These current peaks should be responsible of the highest B-field values recorded. Unfortunately, at the time of writing, it was not possible to precisely correlate the measured B-field values with currents and speed due to the unavailability of a complete and robust data acquisition system.

In a number of cases the measurements based on the weighted peak method (WPM) resulted above 100%, so above the recommended reference level. They were found in PHEVs and only in one EV, the latter with a particular setting aimed at maximizing the energy regeneration during coasting. These peaks above 100% should be investigated more deeply to answer the following open questions: Are these exceedances real or an artefact of the measurement method or the instrumentation? Does their appearance follow a specific trend or are they correlated with specific operations? To clarify these aspects, B – field values in the time domain should be acquired at a proper acquisition frequency and then correlated and synchronized with speed and currents over time.

This exploratory research revealed the limitations of the instrumentation in characterizing the magnetic field environment. In fact, the instrument had a resolution of 5 Hz within the range 25 – 2 kHz and of almost 1 kHz within the range 4.8 – 400 kHz. It turned out that this resolution might not be sufficient to properly characterize the B-field due to the fact that instantaneous high peak values might not be recorded. As a consequence, it is very likely that the measured values underestimate the real value of the magnetic field due to low frequency resolution of the instrument EHP50G.

Actually the recently published standard IEC TS 62764 – 1:2019 that describes how to measure magnetic fields inside a vehicle, does not specify any requirement in terms of frequency resolution, while the Chinese procedure GB/T 37130-2018 requires the use of an instrument with 1 Hz resolution up to 2 kHz, 5 Hz within the range 5 kHz – 50 kHz, and 50 Hz between 50 kHz – 400 kHz.

Furthermore, in the time domain (WPM), the EHP50G provides output values only as the percentage of the ratio between the measured field and the RL of the field. Raw B - field values are not available, confirming that the probe used is not the best choice for these measurements.

The challenges in terms of measurements were addressed in the framework of the collaboration with the ENEA agency. Joint test campaigns on e-Golf and Jaguar I Pace included a comparison between measurements with two identical calibrated probes EHP50G in order to check reproducibility. Test campaign on Jaguar I Pace was also organised with the aim to acquire B-field values in the time domain by means of the ELT – 400 probe, which belonged to ENEA agency and to demonstrate a possible underestimation of values recorded with the instrument used previously. The results object of this collaboration will be later published.

7 Recommendations

The tendency to increase the battery capacity of EVs to attain greater range raises other potential issues: high currents flowing inside vehicles that can produce potentially high magnetic fields that should be properly evaluated. In view of a future massive production of electrified vehicles and in the absence of specific regulations, a standard procedure to assess low frequency magnetic fields inside vehicles to be used for regulatory purposes is necessary to:

- Introduce a clear regulatory framework giving certainty to the market players investing in the development of electrified vehicles
- Reduce the risk of having vehicles with low safety standards in which the users are exposed to potential hazards (e.g. low cost models obtained by reducing the shielding of components generating EMFs.)

At the moment there are a few procedures recently published by international organizations and standardization bodies that are recommended to assess the EMFs generated by electric vehicles. However, no regulation requires mandatory measurement of magnetic field at vehicle type approval. These procedures were published starting from the end of 2018 but there are still open questions about their completeness and significant room for improvement. In general, they are very similar in terms of vehicle operating conditions, vehicle set-up and background requirements. The difference between them mainly lies in the level of detail used in describing the number of measurements per location, the measurement method and the instrument requirements.

This study, started at the beginning of 2018 and carried out before the end of 2019 the publication of the final version of these procedures, provides valuable experimental data and inputs for the development of a harmonized procedure for regulatory purposes. The results confirm that test procedures to measure magnetic fields inside vehicles should cover maximum acceleration/deceleration capabilities, with worst-case settings selected. In fact, acceleration and braking phases, rather than constant speed phases, are responsible for the highest peaks of current and consequently for higher values of B-field; B-field values may also vary according to the vehicle configuration and use during the test (air conditioning, regenerative breaking). The correlation between measured B-field values and the operating conditions and use of the vehicle should be further investigated but this requires also the development of ad-hoc tools to acquire and synchronize all the relevant parameters (speed of the vehicle, currents flowing in the cables,…).

Practical cases and measurements reported in this document have revealed that strict requirements for instruments in terms of frequency resolution are needed to properly characterise the magnetic field in the frequency domain. Furthermore, time domain assessment conducted with WPM is necessary to avoid overestimation and should be correlated with other quantities such as speed, acceleration, deceleration and current. The characterization should include also different categories of vehicles such as motorcycles, buses, trucks, and supercars.

The study also identified a number of issues concerning data acquisition and instrumentation that provide useful input for improving future standards:

- There are no commercial solution readily available at the moment for the acquisition and synchronization of all the parameters needed to correlate the measured B-field values with the vehicle operating conditions (vehicle speed, power, currents,…). One of the issues is that the values in principle available from the electronic control unit are encrypted and not easily readable.
- For the assessment in the frequency domain hundreds of spectra are acquired per each measurement. This represents a challenge for data analysis and interpretation. Defining a standard methodology to acquire and process the data would promote the development of ad-hoc software for the processing of the data for the specific application.
- The instrumentation used had limited frequency resolution that might not be sufficient for an accurate measurement in the frequency domain, and also did not provide raw B-field values in the time domain, limiting the possibilities of post-processing. Ad-hoc requirements for instruments to be used for this specific application are needed.

References

[1] A. Tsakalidis and C. Thiel, *Electric vehicles in Europe from 2010 to 2017: is full-scale commercialisation beginning?* 2018.

[2] A. R. Ruddle, "Preliminary estimates of electromagnetic field exposures due to advanced vehicle technologies," IEEE, 2017.

[3] A. R. Ruddle, "Towards a risk-based approach for the design of highly resilient future vehicles," in *7th Transport Research Arena TRA 2018, April 16-19, 2018, Vienna, Austria*, 2018, pp. 1–10.

[4] P. Concha Moreno-Torres, J. Lourd, M. Lafoz, and J. R. Arribas, "Evaluation of the magnetic field generated by the inverter of an electric vehicle," *IEEE Trans. Magn.*, vol. 49, no. 2, pp. 837–844, 2013, doi: 10.1109/TMAG.2012.2214787.

[5] A. R. Ruddle, R. Armstrong, and A. Galarza, "HEMIS Project (Electrical Powertrain HEalth Monitoring for Increased Safety of FEVs): Limitations of Electromagnetic Standards for Vehicles Equipped with Electrical Powertrain," in *Electric Vehicle Systems Architecture and Standardization Needs*, B. Müller and G. Meyer, Eds. Cham, Switzerland: Springer International Publishing, 2015, pp. 105–115.

[6] EC, "1999/519/EC Council recommendation of 12 July 1999 on the limitation of exposure of the general public to electromagnetic fields (0 Hz to 300 GHz)," *Off. J. Eur. Communities*, vol. 199, pp. 59–70, 1999.

[7] ICNIRP, "Guidelines for limiting exposure to time varying electric, magnetic and electromagnetic fields (up to 300 GHz)," *Health Phys.*, vol. 74, no. 4, pp. 494–522, 1998.

[8] ICNIRP, "Guidelines for limiting exposure to time-varying electric and magnetic fields (1 Hz TO 100 kHz)," *Health Phys.*, vol. 99, no. 6, pp. 818–836, 2010.

[9] EU, "Directive 2013/35/EU of the European Parliament and of the Council of 26 June 2013 on the minimum health and safety requirements regarding the exposure of workers to the risks arising from physical agents (electromagnetic fields)," *Off. J. Eur. Union*, vol. 2013, no. June, pp. 1–21, 2013.

[10] IEC, "IEC TS 62764-1 Measurement procedures of magnetic field levels generated by electronic and electrical equipment in the automotive environment with respect to human exposure - Part 1: Low frequency magnetic fields." 2019.

[11] A. Vassilev, A. Ferber, C. Wehrmann, O. Pinaud, M. Schilling, and A. R. Ruddle, "Magnetic field exposure assessment in electric vehicles," *IEEE Trans. Electromagn. Compat.*, vol. 57, no. 1, pp. 35–43, 2015.

[12] R. A. Tell, G. Sias, J. Smith, J. Sahl, and R. Kavet, "ELF magnetic fields in electric and gasoline-powered vehicles," *Bioelectromagnetics*, vol. 34, no. 2, pp. 156–161, 2013, doi: 10.1002/bem.21730.

[13] R. Hareuveny, M. N. Halgamuge, Y. Yaffe, and Y. Tzabari, "Characterization of extremely low frequency magnetic fields from diesel, gasoline and hybrid cars under controlled conditions," *Int. J. Environ. Res. Public Health*, vol. 12, pp. 1651–1666, 2015, doi: 10.3390/ijerph120201651.

[14] E. Karabetsos, E. Kalampaliki, and D. Koutounidis, "Testing hybrid technology cars: Static and extremely low-frequency magnetic field measurements," *IEEE Veh. Technol. Mag.*, vol. 9, no. 4, pp. 34–39, 2014, doi: 10.1109/MVT.2014.2360651.

[15] R. A. Tell and R. Kavet, "Electric and magnetic fields < 100 kHz in electric and gasoline-powered vehicles," *Radiat. Prot. Dosimetry*, vol. 172, no. 4, pp. 541–546, 2016.

[16] P. M. Concha, S. Member, P. Velez, M. Lafoz, and J. R. Arribas, "Passenger exposure to magnetic fields due to the batteries of an electric vehicle," *IEEE Trans. Veh. Technol.*, vol. 65, no. 6, pp. 4564–4571, 2016.

[17] O. Pinaud, O. Chadebec, L. L. Rouve, J. M. Guichon, and A. Vassilev, "Forward model computation of magnetostatic fields inside electric vehicles," *IEEE Trans. Magn.*, vol. 50, no. 2, pp. 985–988, 2014, doi: 10.1109/TMAG.2013.2283913.

[18] M. Havas, S. Shum, and R. Dhalla, "Passenger Exposure to Magnetic Fields on go- Trains and on Buses, Streetcars, and Subways run by the Toronto Transit Commission, Toronto, CANADA," in *Biological Effects of EMFs, 3rd International Workshop*, 2004, pp. 1065–1071.

[19] M. N. Halgamuge, C. D. Abeyrathne, and P. Mendis, "Measurement and analysis of electromagnetic fields from trams, trains and hybrid cars," *Radiat. Prot. Dosimetry*, vol. 141, no. 3, pp. 255–268, 2010, doi:

10.1093/rpd/ncq168.

[20] N. G. Ptitsyna, A. Ponzetto, Y. . Kopytenko, V. . S. Ismagilov, and A. G. Korobeinikov, “Electric Vehicle Magnetic Fields and Their Biological Relevance,” *J. Sci. Res. Reports*, vol. 3, no. 13, pp. 1753–1770, 2014.

[21] A. R. Ruddle, L. Low, R. Armstrong, L. Dawson, and A. Rowell, “Recommendations for mitigating low frequency magnetic field exposure in hybrid/electric vehicles,” *2014 Int. Conf. Connect. Veh. Expo, ICCVE 2014 - Proc.*, pp. 86–91, 2014, doi: 10.1109/ICCVE.2014.7297674.

[22] A. R. Ruddle and L. Low, “Evaluating low frequency magnetic field exposure from traction current transients in electric vehicles,” in *2013 International Symposium on Electromagnetic Compatibility*, 2013, pp. 78–83.

[23] A. Vassilev, M. Rickers, A. Ferber, and A. Vogl, “EM-Safety Project Deliverable D2.3, Representative vehicle exposure measurements,” 2012.

[24] C. Wehrmann, “EM-safety Project Deliverable D 3.4 ‘Final report on characterisation and test,’” 2014.

[25] K. Schjølberg-Henriksen, A. Ruddle, L. Low, J. Werner, “EM safety Project Deliverable D1.2 ‘Report on Major Magnetic Contributions Likely to be Dangerous to Health,’” 2012.

[26] V. Sala and A. Ponzetto, “EM-safety Project Deliverable D2.4 ‘Electric Fields (EF) / Electromagnetic Fields Irradiation (as expected in cars) on Mammalian different types of cell lines (FIRMS month 15),’” 2014.

[27] Andreas Vogl, “EM-SAFETY Report Summary,” 2015.

[28] Narda safety Test Solutions, “User’s Manual EHP-50G Electric and magnetic field probe - analyzer from 1 Hz up to 400 kHz.”

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