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Comparison of magnetic induction emissions in electric, hybrid and conventional cars

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The article analyses magnetic induction levels in vehicles with three different drive types: electric, hybrid, and conventional. The aim of the research was to determine the intensity of low-frequency magnetic fields generated by the drive systems and their effect on the driver and passengers of the vehicle. The paper describes methods for measuring magnetic induction at various locations within the vehicle, including the engine compartment and the power supply system. Measurements of magnetic induction were also performed during the charging of an electric car. The research results indicate that the highest magnetic induction occurs in electric cars and in the charging area during charging. In conventional drive cars, magnetic induction is mainly limited to the operation of the alternator. The power of the drive system significantly affects magnetic induction. In the case of measurements of magnetic flux density emitted by the power supply system and drive systems of fully electric and hybrid cars, the studies also showed that the location of elements such as the DC/AC converter and the cables connecting the converter to the electric motor and their distance from the driver's and passenger seats significantly affect their exposure level.

Key words: *electromobility, magnetic flux density, electric drive, hybrid drive, conventional drive*

1. Introduction

The electromagnetic field (also called electromagnetic radiation), abbreviated as EMF, is the effect of electric and magnetic fields. The magnetic field is a manifestation of the electromagnetic field with frequencies in the range from 0 Hz (constant fields) to 300 GHz (microwave radiation). Above the upper limit of the indicated range, the following radiations are distinguished: infrared, visible, ultraviolet, X-ray, gamma and cosmic radiation. Electromagnetic fields are divided into natural and artificially generated. Natural magnetic fields are associated with phenomena occurring in the atmosphere (e.g. lightning during a storm), while artificially generated fields are a manifestation of human activity. They may differ in wavelength and frequency. An alternative quantity to the magnetic field intensity – magnetic induction – is often used to characterize low-frequency magnetic fields. Magnetic induction (B) is a component of the magnetic field, which is measured in teslas (T) or gauss (G). This is a quantity related mainly to the magnetic field, regardless of whether it is constant (e.g. the field of a magnet) or variable (e.g. around a conductor with alternating current). Magnetic induction is presented by formula (1) [7, 12]:

$$B = \mu H \tag{1}$$

where: B – magnetic induction, T, μ – magnetic permeability, T·m/A, H – magnetic field intensity, A/m.

The main difference between electromagnetic field measurement and magnetic flux density measurement is that magnetic flux density measurement deals only with the magnetic component of the field, whereas electromagnetic field measurement includes both electric and magnetic components, often in the context of electromagnetic waves.

It should be emphasized that measuring the electromagnetic field differs significantly from measuring magnetic flux density. EMF measurement encompasses both the electric and magnetic components of the field and is typically used to analyze electromagnetic waves, especially in the high-frequency range. Magnetic induction measurement, on the other hand, concerns only the magnetic component and is primarily used to analyze low-frequency fields, such as those in the immediate vicinity of electrical devices and test vehicles [5–7].

2. Electromagnetic field in motor vehicles

Electric car engines and the AC power supply system emit frequencies from 20 Hz to 600 Hz, depending on the driving mode. Battery charging stations emit EMF with frequencies from 20 kHz to 100 kHz. The vehicle structure is largely made of metal elements, which at operating frequencies of 0.8–150 kHz constitute a barrier against electromagnetic field emissions. The electromagnetic field in electric vehicles ranges from low-frequency fields to microwave radiation. The engines and the inverter with wires in electric cars, as well as the alternator in combustion cars, emit low-frequency magnetic fields, i.e. magnetic induction [6–9, 13, 15].

Main sources of magnetic induction in electric cars:
- Electric motor – in the motor, the flow of current through the stator windings generates a magnetic field that affects the rotor. Since the rotor is often made of magnetic materials (e.g. permanent magnets or ferromagnetic cores), this field creates magnetic induction, which creates torque and drives the wheels.
- High-voltage cables – electrical cables and connections, e.g. between the battery and the inverter, also generate a magnetic field.
- Inverter – controls the flow of current to the motor, converting direct current (DC) from the battery to alter-

nating current (AC). The alternating current in the motor windings creates an alternating magnetic field.
- Batteries and charging systems – although the batteries themselves do not generate an alternating magnetic field (DC), alternating currents can occur during charging (e.g. in chargers).

In a conventional car, the sources of magnetic induction (B) differ from those in an electric car, but they still occur. The main sources are:
- Alternator – the main source of the magnetic field. Inside the alternator, the rotor with the winding generates a variable magnetic field.
- Ignition coil and high-voltage wires – change the voltage from 12V to several thousand volts to generate a spark in the spark plug. The flow of current through the coil creates a strong magnetic field, which then disappears, inducing high voltage.
- Starter motor – generates a magnetic field in the windings. Although it works only for a moment, it generates strong magnetic field pulses [1, 2, 15,16, 19–22].

In hybrid vehicles, the classic alternator and starter are replaced by one or more electric motor–generator units, which can function as both a drive motor and a generator to charge the traction battery. These components, such as electric motors, inverters, DC/DC converters, and high-voltage cables, generate magnetic fields due to the flow of current [1, 3].

The scientific literature contains numerous studies on magnetic field emissions from vehicles with different drive types. Tell et al. measured magnetic field intensity in electric and combustion cars, showing that electric vehicles generate significantly higher magnetic fields, especially in the drive systems and passenger compartment. The greatest exposure was in the area around the driver's and front passenger's legs [17].

He et al. studied the effects of static magnetic fields generated by electric vehicles on drivers' cognitive functions. Their results suggest that even fields with intensity consistent with applicable standards may affect the nervous system and reaction time during long-term exposure [6].

In Poland, studies by Gryz et al. found higher magnetic induction levels in hybrid and electric vehicles than in conventional vehicles. It was indicated that the main sources of emissions are inverters, high-voltage cables, and electric motors, and that field values in the area of the driver's feet can reach 10–15 μT [7].

In turn, Wang et al. [20] conducted long-term monitoring of low-frequency magnetic fields in electric vehicles and observed significant variations in emission levels depending on driving mode, load and arrangement of drive system components. The highest values were recorded during acceleration and battery charging [21].

The conclusions from the cited studies clearly indicate that electric and hybrid vehicles exhibit higher levels of magnetic field emissions, and user exposure is significantly influenced by the power of the drive system, component arrangement, and distance from the field sources [6, 22].

3. The effects of electromagnetic fields on humans

An electromagnetic field can stimulate excitable tissue by inducing electric currents in the body. This phenomenon is most significant at frequencies lower than several hundred kHz. In addition, tissue heating occurs due to the absorption of field energy (the so-called thermal effect), and the most important aspect is its occurrence at frequencies above 1 MHz. Moving in an electromagnetic field can also cause, among other things, dizziness, nausea, and impaired eye-hand coordination. They stop after moving away from the source. An electromagnetic field can cause undesirable changes in the body's functioning. The results of scientific research indicate that possible effects of electromagnetic fields include disorders of the nervous, cardiovascular, and immune systems, neoplastic processes, and subjective complaints such as headaches, fatigue, and memory disturbances. A large number of diseases are reported in people living near transmission lines, electricity generators and similar interfering devices. A 1979 study by physicist Ed Leeper showed that children exposed to just 0.3 μT had twice the incidence of leukemia. In 1998, the New York State Department of Health repeated the study and confirmed the previous study's results. Studies show that the protective threshold for direct exposure to an AC electric field should not exceed 5 V/m at ground potential and 1.5 V/m without ground potential. The AC magnetic field emission should not exceed 0.1 μT. [6–11, 13, 14, 22, 23].

4. Apparatus and subject of research

The measurements were carried out using two electromagnetic field meters, TM-191 and TM-196. The TM-191 meter operates in the range of 30–300 Hz, while the TM-196 meter operates in the range from 10 MHz to 8 GHz.

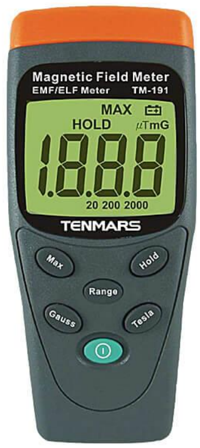

Fig. 1. Electromagnetic field meter TM-191 [17]

Table 1. Technical parameters of the TM-191 electromagnetic meter [17]

Feature	Value
Measured field	Very low frequency (LF) magnetic field 30–300 Hz
Measurement method	Single-axis sensor
Measurements	For frequencies 30–300 Hz
H (magnetic field)	200.0/2000 mG; 20.00/200.0 μT
Accuracy	±2.5% for frequencies 50/60 Hz
X, Y, Z measurement	none

Bench measurements were performed, as were magnetic induction measurements during charging of an electric vehicle at a charging station. To avoid interference with the measurements, the radio and other electronic devices were turned off for the duration of the measurement.

Fig. 2. Electromagnetic field meter TM-196 [17]

Table 2. Technical parameters of the TM-196 electromagnetic meter [17]

Feature	Value
Measured field	Radio frequency electromagnetic field 10 MHz–8 GHz
Measurement method	Digital measurement 3-axis
Directional characteristic	Isotropic, triaxial
CAL coefficient	Settable in the range 0.10–9.99 (default 1)
Measurements	CW signal (f > 50 MHz)
E (electric field)	38.0 mV/m; 11.0 V/m
H (magnetic field)	53.0 μA/m.; 28.64 mA/m
S (power density)	0.1000 μW/m^2; 309.3 mW/m^2
Dynamic ranges	0.1000 μW/cm^2; 30.93 μW/cm^2
Accuracy	75 dBm
Isotropic deviation	Absolute error ±0.1 dBm at 1 mV/m and 2.45 GHz
X, Y, Z measurement	Selection: all axes, X-axis, Y-axis or Z-axis

The research object is three passenger cars. A conventional drivetrain car of the Dacia Sandero III brand with a 1.0 Tce petrol engine with a turbocharger with an output of 67 kW. An electric car of the Dacia Spring brand with a synchronous motor with a permanent magnet with an output of 33 kW [4, 5]. A hybrid drive car of the Toyota

a) Conventional drive vehicle

Fig. 3. Conventional drive car Dacia Sandero

Table 3. Technical data of the Dacia Sandero [5]

Model	Dacia Sandero III Hatchback; 2021
Drivetrain type	ICE
Engine	1.0 Tce petrol turbocharged
Displacement	999 cm^3
Engine power	67 kW, 90 HP for 4600 rpm
Torque	160 Nm for 2100–3750 rpm
Drive	Front axle
Range	962 km
Current weight	1152 kg

C-HR brand with a 1.8 internal combustion engine with an output of 72 kW and an electric motor with an output of 53 kW. The total power of the hybrid system is 90 kW [18]. All vehicles were manufactured in 2021 and had Crossover bodies. However, this brand does not offer a hybrid car, which is why a Toyota hybrid drive [3] was selected for comparison.

b) Battery electric vehicle

Fig. 4. Electric drive car Dacia Spring

Table 4. Technical data of the Dacia Spring [4]

Model	Dacia Spring Crossover Electric; 2021
Drivetrain type	Electric
Engine	Permanent magnet synchronous
Engine power	33 kW, 45 HP for 3000–8200 rpm
Torque	125 Nm for 500–2500 rpm
Drive	Front axle
Battery	lithium-ion
Gross battery capacity	27 kWh
Charging time socket/fast	13 h/1h
Range	230 km
Own weight	920 kg

c) Hybrid electric vehicle

Fig. 5. Toyota C-HR hybrid car – view under the engine cover

Table 5. Technical data of the Toyota C-HR [18]

Model	Toyota C-HR Crossover SUV; 2021
Drivetrain type	Hybrid (HEV)
Engine	1.8 Hybrid
Engine system power	Power 90 kW, 122 HP at 5200 rpm
Petrol engine power	72 kW, 98 HP at 3600 rpm
Petrol engine torque	142 Nm at 3600 rpm
Electric engine power	53 kW, 72 HP
Electric engine torque	163 Nm
Battery	lithium-ion
Gross battery capacity	1 kWh
Gearbox type	Automatic e-CVT
Range	895 km
Current weight	1380 kg

5. Research

5.1. Stationary measurements

a) Conventional drive vehicle

In a conventional drive car, magnetic induction measurements were taken in the vicinity of the alternator. Each time, 20 measurements were taken directly at the device and at distances of 0.2 m and 0.5 m. During the measurements, the temperature was about 15°C.

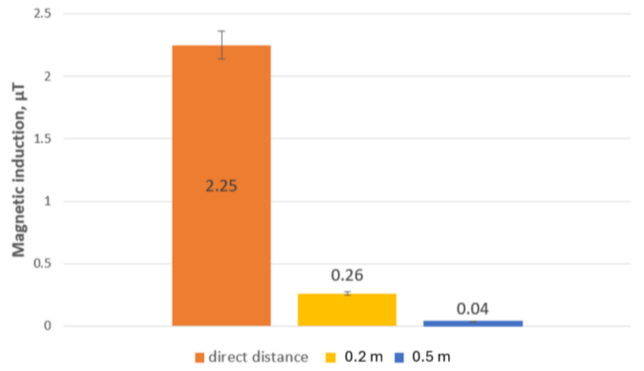

Fig. 6. Magnetic induction in the vicinity of the alternator – conventional vehicle

During bench tests, the magnetic induction in a conventional car with an ICE near the alternator was recorded at a level of 2.25 µT, which at a distance of 20 cm was already below 1 µT.

b) Battery electric vehicle

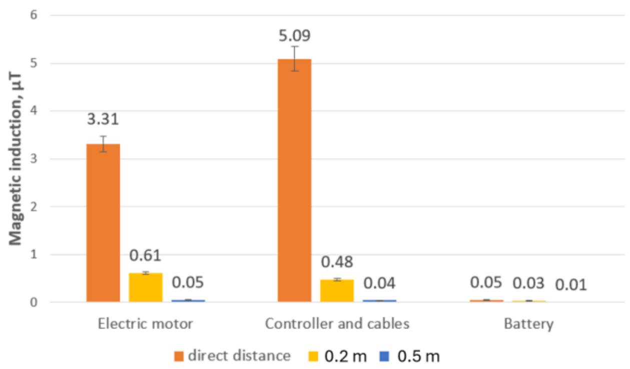

Fig. 7. Magnetic induction – electric vehicle

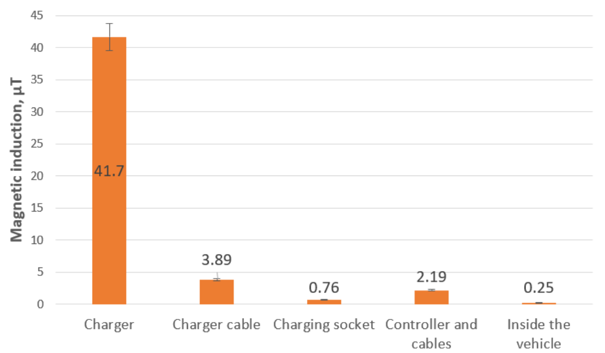

Fig. 8. Magnetic induction in the area of the charger during charging of an electric vehicle

In the electric car, during the bench test, magnetic induction occurred in the vicinity of the inverter and cables (5 µT) and near the engine (3.3 µT), while in the case of the alternator in a combustion engine vehicle, after moving away from the source by 20 cm, it was only from 0.4 µT to 0.6 µT. The highest magnetic induction was recorded during charging of the electric car in the vicinity of the charger and high-voltage cables. It amounted to 41.7 µT. At the charger cable, it was 3.9 µT, and in the vicinity of the inverter and vehicle cables, 2.2 µT.

c) Hybrid electric vehicle

In the hybrid car, magnetic induction measurements were taken in the vicinity of the generator, electric motor, inverter, and high-voltage cables. Each time, 20 measurements were taken directly at the device and at distances of 0.2 m and 0.5 m. During the measurements, the temperature was around 15°C.

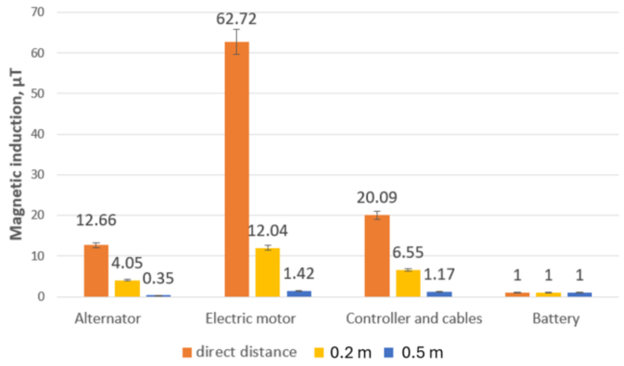

Fig. 9. Magnetic induction – hybrid vehicle

During tests in a hybrid car, magnetic induction of 62.7 µT was recorded near the electric motor, 20 µT near the inverter and cables, and 12.6 µT near the generator. At a distance of 20 cm from the sources, it was: 12.4 µT for the engine, 6.5 µT for the inverter, and 4 µT for the generator.

5.2. Measurements while driving

The magnetic field intensity measurements were conducted inside each of the three vehicles across four driving conditions. The measurements were taken with a TM-196 three-axis electromagnetic field meter operating in the high-frequency range. The first measurements were taken in city traffic at 30 km/h and 50 km/h, then in motorway traffic at 100 km/h and 140 km/h. During measurements at 30 km/h, only the electric motor was running in the hybrid car; at other speeds, the combustion engine was running. Each time, 20 measurements were taken. The measurements were taken in the afternoon and evening, with temperatures around 15°C. There was no wind and no precipitation. There was no snow cover. The meter was mounted near the driver's seat. To avoid interference with the measurements, the radio and other electronic devices were turned off for the duration of the measurement. The results presented are the result of the X, Y, and Z axes (geometric sum). Measurements are presented as an arithmetic mean of the collected results, excluding the lowest and highest values. Error bars are marked on the graphs.

a) 30 km/h

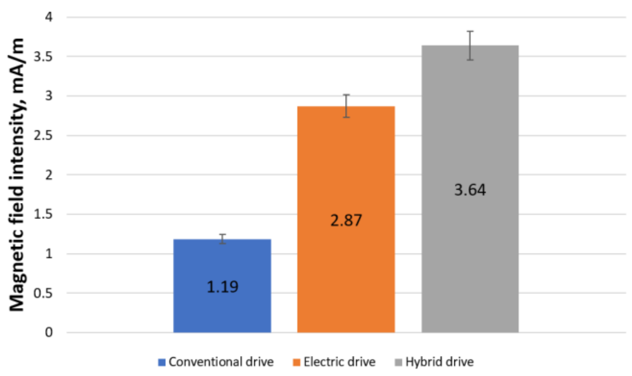

Fig. 10. Summary results of magnetic field intensity measurements at vehicle speeds of 30 km/h

b) 50 km/h

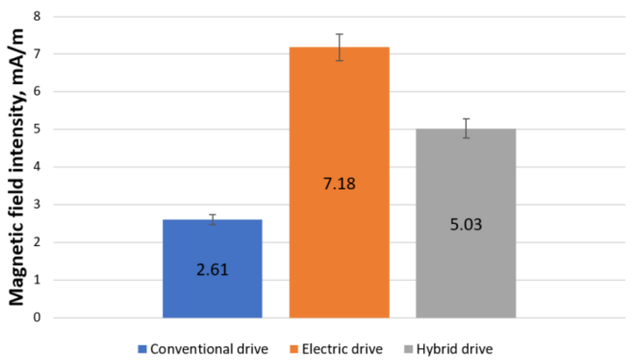

Fig. 11. Summary results of magnetic field intensity measurements at vehicle speeds of 50 km/h

During city driving, the magnetic field strength was highest for the hybrid vehicle (3.6 mA/m), slightly lower for the electric vehicle (2.8 mA/m), and lowest for the conventional vehicle (1.2 mA/m) at 30 km/h. At 50 km/h, the values were highest for the electric vehicle (7.2 mA/m), followed by the hybrid vehicle (5 mA/m), and lowest for the conventional vehicle (2.6 mA/m). The hybrid vehicle emitted lower values when the conventional rather than the electric system operated at higher speeds.

c) 100 km/h

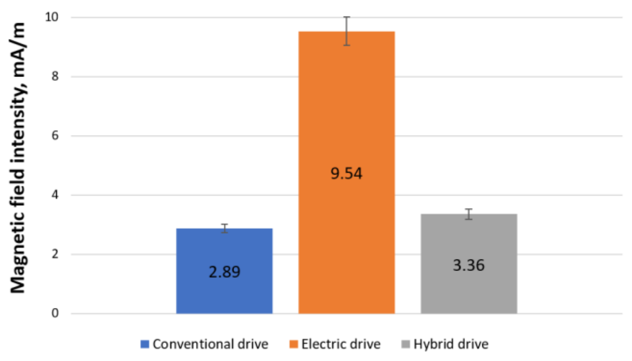

Fig. 12. Summary results of magnetic field intensity measurements at vehicle speeds of 100 km/h

d) 140 km/h

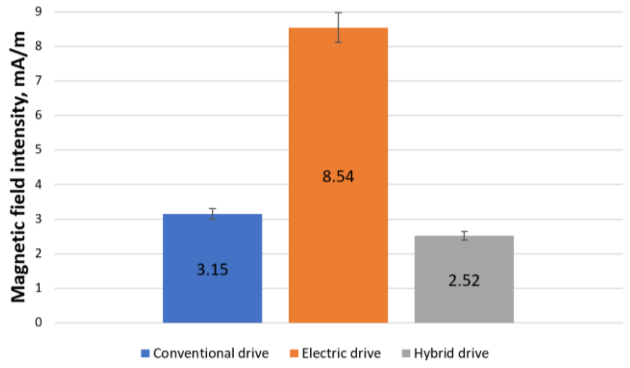

Fig. 13. Summary results of magnetic field intensity measurements at vehicle speeds of 140 km/h

During motorway driving at 100 km/h, the magnetic field strength was highest for the electric vehicle (9.7 mA/m), lower for the hybrid (3.4 mA/m) and lowest for the conventional vehicle (2.9 mA/m). At 140 km/h, it was the highest for the electric vehicle (8.5 mA/m), lower for the conventional vehicle (3.1 mA/m) and lowest for the hybrid (2.5 mA/m).

6. Conclusions

The conducted tests allowed obtaining different values of magnetic flux density depending on the type of vehicle, the measurement location, and the distance from the source of field emission. In a car with a conventional drive (Dacia Sandero), the highest value of the magnetic field was recorded in the immediate vicinity of the alternator and amounted to 2.25 μT. This value decreased rapidly with increasing distance–already at a distance of 20 cm the magnetic field dropped below 1 μT, which indicates a limited range of this source and low exposure of the driver and passengers to magnetic flux density.

In the electric vehicle (Dacia Spring), the field values were much higher. During operation of the drive system, the maximum magnetic flux density was 5.0 μT in the vicinity of the inverter and high-voltage cables, and 3.3 μT at the engine. After moving away by 20 cm, these values dropped to 0.4–0.6 μT, confirming the strong dependence of the field intensity on distance from the source. However, the highest magnetic field emission was recorded during vehicle charging, when the field reached 41.7 μT in the immediate vicinity of the charger, 3.9 μT at the charging cable, and 2.2 μT in the inverter area inside the vehicle. The measured value of 41.7 μT indicates a potential health risk from prolonged exposure in the immediate vicinity of the charger. The highest magnetic field values were recorded in the hybrid vehicle (Toyota C-HR). The field strength in the area of the electric motor was 62.7 μT. Values of around 20 μT were measured near the inverter and high-voltage cables, and 12.6 μT near the generator. Even at a distance of 20 cm from the source, the values were significant: 12.4 μT, 6.5 μT and 4.0 μT respectively. Such high values in a hybrid vehicle may be due to the drive system's higher power and the more complex electrical system configuration compared to a lower-power electric vehicle. Summarizing the results of measurements during driving, the highest magnetic field strengths occur in electric vehicles, especially at higher speeds, due to the continuous, intensive operation of the electrical system, including the inverter, engine, and high-voltage cables. In hybrid vehicles, the magnetic field is higher at lower speeds because the electric motor is used more often in urban conditions. At higher speeds, the hybrid drive system primarily runs on the combustion engine, reducing field emissions. Conventional vehicles generate the lowest values, because their field sources–such as the alternator or ignition system – work less intensively and have a smaller share in generating the magnetic field compared to electric vehicles. The comparative analysis showed that electric and hybrid cars generate significantly higher magnetic fields than conventional-drive vehicles. The value of the magnetic flux density is significantly influenced by the power of the drive system and the location of components, such as the electric motor, inverter, or high-voltage cables, relative to the vehicle users. In addition, the measurements confirmed that the field intensity decreases exponentially with distance from the source, which is crucial for protecting the driver's and passengers' health. The field values measured in the immediate vicinity of the devices, especially during charging of the electric vehicle or operation of the electric motor in a hybrid vehicle, approach the limits permitted by international standards. Therefore, the choice of the drive system components' locations and the design of their shields should aim to minimize the user's exposure to the magnetic field. All observed values are below the permissible levels specified by the International Commission on Non-Ionizing Radiation Protection (ICNIRP), which sets a limit of 100 μT (for magnetic flux density) or about 80 mA/m (for field intensity) for magnetic fields at vehicle frequencies (approximately 50–60 Hz). This means that despite clear differences between vehicles, the level of exposure of drivers and passengers remains within safe limits. However, long-term exposure in the immediate vicinity of some sources (e.g. a charger when charging an electric vehicle) may require further monitoring, especially in the context of possible effects on particularly sensitive individuals.

Nomenclature

AC alternating current
DC direct current
EMF electromagnetic field
ICE internal combustion engine

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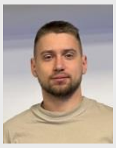

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