



Measurement of Electromagnetic Fields Exposure to Humans from Electric Vehicles and Their Supply Equipment

Gowthama Priya Punniya Murthy, Gowri Sree Varadarajan *

Division of High Voltage Engineering, Department of Electrical and Electronics Engineering, College of Engineering Guindy, Anna University, Chennai 600 025, India

ARTICLE INFO

Keywords:

Electric field
Magnetic field
Electric vehicles
Electric vehicle supply equipment
Long-term exposure
EMF measurement
Finite element method

ABSTRACT

Electric Vehicles (EVs) represent a progressive approach to fostering a healthy and sustainable transportation future on Earth. Intended for mitigating global warming by virtue of decarbonizing transportation sector. Besides being environmentally beneficial, electrification in transportation necessitates a study of non-ionizing Electro-magnetic Fields (EMF). Despite extensive research, the health effects related to long-term exposure to EMF remain inconclusive. The main aim of this research is to share and disseminate measurement findings of EMF emission from EVs and their Electric Vehicle Supply Equipment (EVSE). The specification of the measuring instrument, methodology adhered to measurement, and observed results have been discussed. Measurements have been carried out at different EVs and EVSEs in and around Chennai city, up to 400 kHz frequency band. To analyze human exposures, Electric Field Intensity (E) and Magnetic Flux Density (B) have been measured in the vicinity of driver and passenger seats inside EVs during driving condition, furthermore fields near different positions of EVSEs during charging condition. The measured values have been compared with the ICNIRP and IEEE standard recommendations for human external body exposure level. In accordance with the findings, E & B inside EVs fall within the standard limit. The E in the vicinity of EVSE is under standard limit, but at certain places B is concurrently above general public exposure threshold ($>200 \mu\text{T}$). In addition, a preliminary computational analysis has been done using Finite Element Method (FEM). Simulated fields are then compared with measurement readings of AC charger, where the electric and magnetic field magnitudes are relatively higher. With an ever-increasing electrification of vehicle fleets, knowledge of health impacts of long-term exposure to humans can be enhanced through more observational research.

1. Introduction

Electric vehicles have emerged as a new way of transportation to decarbonize the transportation sector by encouraging electric automobiles into the market, presently replacing conventional motor vehicles to a greater extent. Nowadays, EVs have gained increasing positive attention due to the potential health consequences of fuel-based vehicles' tailpipe emissions, such as greenhouse gases, on air quality [1]. In the meantime, owing to the rapid increase in oil and petroleum demand, governments, NGOs, and environmentalists encourage EVs to reduce global warming and to save fuels for future generations [2]. People are switching to EVs more quickly than ever before. There were over 17 million electric cars sold worldwide, and the share of the global car market surpassed 20 % for the first time in 2024. In the first three months of 2025, sales of electric cars increased 35 % year-on-year. Despite considerable uncertainty, the market share of electric

automobiles is expected to surpass 40 % by 2030 as they become more reasonably priced in more areas, according to a survey by the International Energy Agency (IEA) [3]. Manufacturers are introducing cleaner and advanced new embedded innovations in electrical vehicles to meet this need. A vast array of intricate electronic and electrical sub-assemblies with varying power levels is accommodated by EVs. This includes plug-in Battery Electric Vehicles (BEVs), plug-in hybrid electric vehicles, hybrid electric vehicles, and so on [4]. Developments in battery technology, charging systems, power electronics, and thermal management, assessing their impact on EV performance and scalability. Emerging trends include AI-based energy management, vehicle-to-grid (V2G) integration, and renewable energy adoption for grid-interactive EV operation [5].

The EV advancements must be regulated in tandem with their recharging systems. The recharging system should effectively offer higher charging currents and wattage for substantially greater battery

* Corresponding author.

E-mail addresses: gpgotama@gmail.com (G.P. Punniya Murthy), gowri06@yahoo.com (G.S. Varadarajan).

<https://doi.org/10.1016/j.measurement.2025.119378>

Received 28 June 2025; Received in revised form 13 October 2025; Accepted 15 October 2025

Available online 21 October 2025

0263-2241/© 2025 Elsevier Ltd. All rights are reserved, including those for text and data mining, AI training, and similar technologies.

capacity of EVs, such as long-range Sports Utility Vehicles (SUVs), heavy-duty trucks and buses, and so on [6]. In order to fulfill the demand, equivalent Electric Vehicle Charging Stations (EVCS) are being established in key areas for charging in public and workplaces as a supplement to residential charging [7]. Public charging stations are a key factor in facilitating the adoption of EVs, especially in urban areas where access to domestic charging is more limited. By 2022, there were 2.7 million public charging stations globally; since 2022, it has doubled to reach more than 5 million. By 2035, it might have increased sixfold, assisting mass-market consumers in transitioning to electric transportation [8].

In a charging station, a charge point or EVSE is a power supply device that provides electrical power for plug-in electric vehicles. Plugging and unplugging connectors into the vehicles requires proper alignment during the EV charging process. An effective charging procedure is ensured by this alignment, which permits power to flow efficiently from the charger to the vehicle's battery [9]. Direct Current (DC) and Alternating Current (AC) charging stations are the two primary varieties of EVSE. It is characterized as onboard and offboard. Charging methods can be classified as conductive charging, battery swapping, and wireless or inductive charging. Most EVs have a conductive charging technique [10]. There are three charging levels for conductive chargers (Levels 1 to 3) according to SAE J1772 [11,12] and four modes (Modes 1 to 4) in accordance with IEC 61851-1 [13]. Wireless charging methods use time-varying magnetic fields to transfer power from the grid to the EV battery. Wireless charging is categorized into three different types, such as capacitive, inductive, and resonant-inductive [10].

1.1. Standards and Regulations

The simplest form of Level 1 charging uses a 120 V 1-phase AC connection to a standard residential electrical outlet capable of supplying 12/16 A of current, and power drawn is usually around 1.44/1.9 kW while charging. Level 2 semi-fast 1-phase AC charging requires 208/240 Volts, 12/80 A, and 2.5/19.2 kW power connection with a significantly reduced charging time. Both level 1 and 2 based EVs use an on-board inverter to switch to DC power that charges the batteries [9]. IEC 62196-1 and 62196-2 are the common standards adopted by all countries for conductive AC EV charging connectors Type 1 and 2 [14,15]. Meanwhile, IEC 62196-3 and 61851-23 are for Level 3 (DC) and use an off-board inverter, which facilitates fast charging by delivering high power directly into an EV's battery system [16,17]. Its two different specifications are 50 kW/400–500 V/100–125 A and 120 kW/300–500 V/300–350 A. Three different connectors are available for DC fast-charging equipment made by different manufacturers, like Combined Charging Systems (CCS). The first one is the CHAdeMO that Nissan, Mitsubishi, and Kia use. The second one is the SAE Combo that American and European manufacturers, like Mercedes-Benz, BMW, and Chevrolet, employ. The third one is the Tesla supercharger (NACS), which is only found on the Tesla Model S. An adapter that enables Tesla owners to use CHAdeMO devices has also been announced. DC Extreme Fast Charging (XFC) delivers above 350 kW and is an ultra-fast charging EVSE for 1000 V_{dc} commercial off-board vehicles. The exact rating depends on the model, make, and country or location of charger usage [10].

As per the Bureau of Indian Standards (BIS), the IS17017 series for AC charging is the base for India's electric vehicle conductive charging system specifications [18]. The fundamental features of all-electric vehicle charging systems are provided by IS 17017 Part 1. An AC EVSE and specific AC connector must adhere to IS17017 Part 2. Both AC and DC EVSE must follow the technical standards IS17017 Parts 21 & 22. Additional Indian standards for AC EVSEs have been approved for light EVs and e-cars. As per the BIS for DC Charging, IS17017 Part 23 describes the requirements for DC charging stations with a power output of 50 kW to 200 kW. IS17017 Part 25 provides DC low power of less than 7 kW for light EVs. Due to the requirement for digital communications between the DC EVSE and the EVs, data communication standards are

specified in IS17017 Part 24 [19]. IS17017 Part 21 Section 1 adopted from IEC 61851-21-1 describes Electromagnetic Compatibility (EMC) requirements for on-board chargers [20], and IS17017 Part 21 Section 2 adopted from IEC 61851-21-2 describes EMC requirements for off-board chargers [21]. While the standards fall under the exclusive control of the Central Electricity Authority, the Automotive Research Association of India published Automotive Industry Standard AIS 138 parts 1 & 2 [22], which is adapted from the IEC and International Organization for Standardization series [23].

1.2. EMF from EV and EVSE – An Inevitable

Since EVs and EVSEs range in high power consumption, electromagnetic emission from these systems is high; it may degrade their own system, or it will disturb neighborhood system performance and also affect the environmental living beings. Electromagnetic Interference (EMI) is one of the main issues in modern electronic circuits. Modern EVs face considerable EMI challenges arising from high-power electronics such as battery, motor and converters that generate high-frequency harmonics. Both radiated and conducted emissions may impair system reliability, while charging operations introduce additional EMI that can degrade wireless communication performance [24]. Highlighting EMC and EMI issues for Full Electric Vehicles (FEVs), noting gaps in current Automotive EMC Standards due to high-power inverters and a concern about passenger exposure to high-frequency fields. The deployment of FEVs has raised concerns about occupants being exposed to high electromagnetic fields, prompting the development of in-vehicle EMF measurement standards [25]. WPT systems in EVs transfer energy via magnetic fields, but leakage fields introduce EMF and EMI challenges. During power transfer, EMF exposure may pose risks to humans due to the strong magnetic fields, while EMI arising from harmonic magnetic fields can interfere with nearby electronic devices. Therefore, before WPT systems can be widely commercialized, both EMF and EMI challenges must be effectively addressed, with strict compliance to relevant regulatory standards [26]. According to SAE J2954, EMFs from EV wireless charging systems are evaluated through bench testing and in-vehicle testing to verify compliance with EMC and safety standards [27]. Despite naturally occurring electromagnetic noise arising mainly from celestial and terrestrial sources (cosmic, solar, lightning noise, etc.) causing electromagnetic interference in the atmosphere, man-made EMI causes much more disturbance to the environment. As we all are living in the modern digital era, man-made EMI arises from electromagnetic interactions in circuits and systems, causing inter and intra electromagnetic interference by both conductive and radiative couplings, which are inevitable. To overcome the interference, the designer must adhere to accepted design guidelines, which lay out specifications for electromagnetic emission control and susceptibility to EMI from other equipment. The design guidelines, performance limits, test and measurement procedures for various electronic, electrical, and electromechanical equipment for different sectors, such as military, medical, industrial, and consumer goods, and so on, have unique standards and regulations. IS 14700 under BIS, UNECE Regulation for Automotive, and IEC 61000/CISPR have a series of international standards, IEEE/ANSI, MIL-STD-461/461G/462, FCC, and so on. That specify standards for Electromagnetic Interference and Compatibility (EMIC). The system's ultimate purpose is to function in a way that achieves effective Electromagnetic Compatibility practices, which are essential to ensure safety [28]. The electrical infrastructure that emits the electromagnetic fields is in close proximity to the humans who utilize this kind of electric transportation. Substantial EMF emission levels can be caused by a variety of factors, such as high AC/DC voltage and current combinations, different configurations, topologies such as battery location, front-wheel drive or rear-wheel drive, various frequency conversions of solid-state devices in power train components on both ends of AC/DC and the distance between the people inside and power equipment [29]. Hence, EVs and EVSEs have been included as one of the

sources in the existing electromagnetic spectrum in addition to a range of other sources, including power lines, appliances, computers, cell phones, Wi-Fi networks, and many other electronic circuits [30]. Though these sources do not create significant health risks for a short duration of exposure, continuous usage of these devices by humans might cause reported symptoms, such as heating of body tissues, headaches, anxiety, infertility, hypersensitivity, depression, cancer, cataracts, and so on. Nevertheless, these reports have not yet been unequivocally validated [31–33].

1.3. EMF Exposure and Biological Implications

WHO 2007a and b have provided risk management guidance, which includes considerations for precautionary measures. By considering the possible harmful effects of electromagnetic field exposure, the International Commission for Non-Ionizing Radiation Protection (ICNIRP) had specified limits to maximum permissible electromagnetic field exposure to the public and occupational personnel. Non-ionizing electromagnetic radiation may not affect human health immediately for a short period of exposure, but for long periods of exposure, the extremely low frequency electric and magnetic fields might cause low-risk health effects to humans [34]. The established short-term health effects from the basis of ICNIRP exposure limits for extremely low frequency (ELF) EMF (1 Hz–100 kHz) are nerve and muscle stimulation, visual disturbances (magnetophosphenes), and tingling, dizziness, or vertigo at very high field strengths. For Radiofrequency (RF, 100 kHz–300 GHz) tissue heating, thermal stress at high whole-body exposures, and localized overheating of tissues (skin, eyes, head, torso) if limits are exceeded. Long-term health effects are cancer and childhood leukemia, which are under investigation and not established. Some epidemiological studies suggest an association with long-term exposure to power-frequency magnetic fields. ICNIRP concluded that current evidence does not confirm a causal link between EMF exposure below guideline limits and cancer [35]. The relationship between environmental exposures, especially extremely low-frequency electromagnetic fields, and cancer in children has been the subject of a substantial amount of research. There is conflicting evidence from many studies indicating electromagnetic field exposure is linked to cancer among children [36]. Two well-established adverse health effects from IEEE C95.1 standard are electrostimulation at low frequencies (below 100 kHz) and tissue heating at higher frequencies (above 100 kHz). In the transition zone (100 kHz – 5 MHz), both mechanisms may occur, with limits based on the more restrictive effect. At radiofrequency, heating effects on skin, eyes, and deeper tissues are the main concern, while at very low frequencies, nerve and muscle excitation, sensory disturbances, and possible cardiac excitation are observed. Additionally, contact with conductive objects can cause shocks, burns, or startle reactions [37].

1.4. Electrical Properties and Its Biological Relevance

The human body is electrical in nature; electrical properties, such as conductivity, permittivity, and permeability of different tissues, were figured out by extensive research. Permittivity and permeability pertain to the tissue's potential for storing electric and magnetic energy, whereas conductivity gauges the rate at which electrical current passes through tissue [38]. Liquid substances, especially electrolytes, reside in the tissues of the human body to facilitate the way they conduct electricity. Numerous biological processes, such as muscle contractions and nerve signal transmission, rely on electric conductivity. Researchers put forward the hypothesis that magnetic fields might be more vital than electric fields. While electric fields are absorbed by the skin and tissues, magnetic fields cause currents to flow through the human body [39,40]. Physical barriers, such as walls, rocks, or trees surrounding homes, attenuate electric fields but not magnetic fields [41]. Electrical properties are highly frequency-dependent; low frequency generally has less detrimental effects than high-frequency voltage and currents. As the

human body is composed of different organs, tissues and sizes, each has different electrical properties. Hence, field coupling and absorption characteristics will vary with female, male, and child. EMF effects on the internal body are measured based on the Specific Absorption Rate (SAR). SAR measures the amount of energy absorbed by biological tissues and is expressed in watts per kilogram (W/kg). EMF coupling and absorption effects in females are increased sensitivity to the reproductive system. Reproductive damage such as decreases the number of follicles in ovaries, increases DNA damage in oocytes, and induce apoptosis and oxidative stress in the endometrium and ovaries. During pregnancy physiological changes in fetuses, leading to increased anxiety-like behaviors in female offspring. Whereas in male EMF coupling and absorption effects are cognitive impairment, decreased sperm function, and impacting male reproductive health [42]. However, the fact of health or biological effects on humans from prolonged EMF exposure is inconclusive [33].

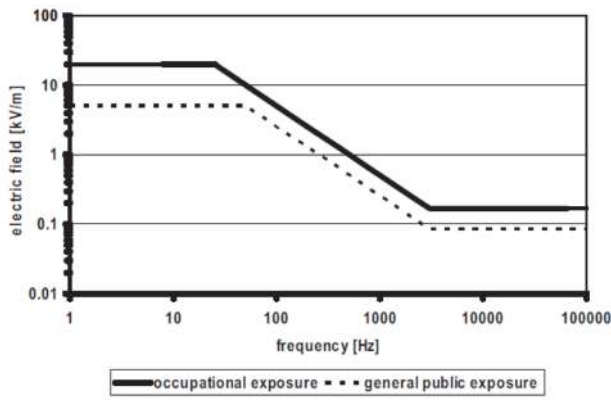
2. Electric and Magnetic Field Measurements

This section describes the measurement of electric and magnetic field exposure levels on the human external body from EVs and EVSEs. The E and B fields have been measured using respective meters across various EV and EVSE models. Subsequently, the corresponding findings are plotted. Further, the measured readings are compared with exposure limits compiled by ICNIRP and IEEE standards, which are depicted in Fig. 2.1 and Fig. 2.2 accordingly. ICNIRP is the primary international scientific organization that sets guidelines for EMF exposure limits based on scientific evidence. Many other organizations, such as Public Health England, EU Directive/OSHA, ARPANSA, etc. also monitor EMF. Based on implication, it gives regulation and standards to be followed. But all national and regional organizations adopt primary standard guidelines from ICNIRP, except United States standards and health organization departments, because they have their own standards, regulations, and safety measurements referred from IEEE/ANSI.

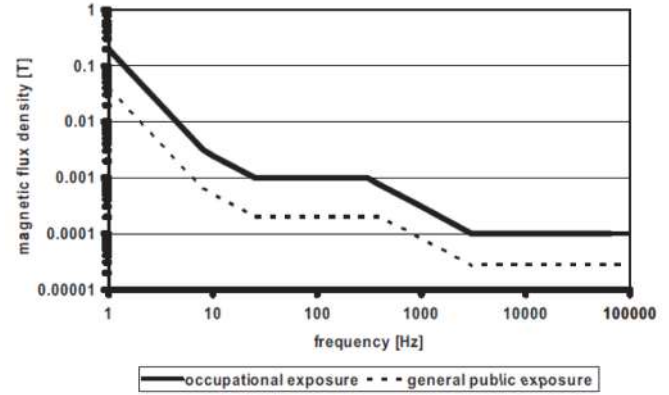
This work aims at analyzing the EMF issues in the popular brand of EVs on the road in present-day Chennai city. Selected four EVs on the basis of being highly available and currently in use in Chennai city. Hence, four EVs were chosen representing each group. EV1 and EV3 are from the same manufacturer but different models, which are the 2nd best-selling in the market. EV2 is a 13-seater vehicle being used in all universities, hospitals, and public places for mobility throughout the day. EV4 is a high end car and a sophisticated vehicle group. Then four EVSEs are selected on the basis of charging capacity from lower to higher wattage range and time taken to charge. The measurement for each model of EVs and EVSEs was planned on a separate day, and on that particular day an average of 5 trials were done for each value reported. Measurements were taken considering adults alone, both male and female. The measurement inside the EV was done with a male driver and a female passenger in normal sitting posture. One female in a standing posture was considered for measuring near EVSE. The age groups are between 34+ and 48 years old.

2.1. Measuring Instruments

Electric Field Meter: The ETS-Lindgren's HI-3638 (Fig. 2.3) is a single-axis instrument used to measure electric field intensity (V/m). This meter ranges from 5 Hz to 400 kHz and complies with IEEE 1140 standards for calibration and measurement procedure. It is useful to measure low field intensity, such as video display terminals, computer monitors, and so on, as well as high field intensity, such as power transmission lines and industrial areas. As per the standard IEEE 1140, the meter was calibrated using a parallel plate arrangement with the probe serving as one of the two plates. The calibration field, E_c is given by the equation $E_c = V/d$ where V is the sinusoidal voltage applied to the parallel plates and d is the parallel plate spacing. The total uncertainty in the value of E_c due to uncertainties in the values of V and d was less than



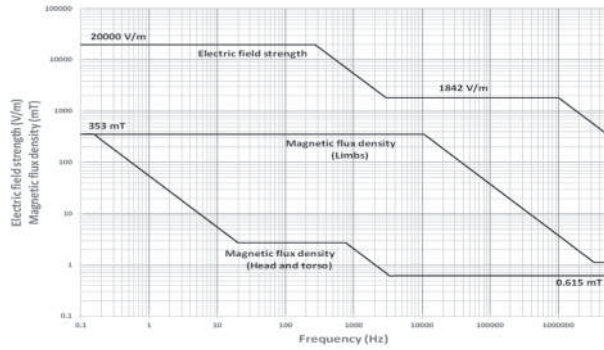
a) Electric Field



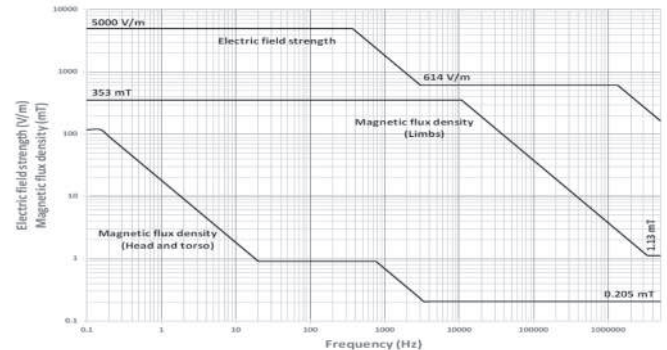
b) Magnetic Field

Fig. 2.1. Graphical representation of electric and magnetic fields exposure limits to humans for external body [1].

Source: ICNIRP 2010] 35



c) Restricted Environment



d) Unrestricted Environment

Fig. 2.2. Graphical representations for exposure reference levels in restricted and unrestricted environments [1].

Source: IEEE Std C95.1, 2019] 38



Fig. 2.3. Electric field meter.

5 %. The maximum electric field strength shall be measured in front of the test object. During measurements, the sensing surface of the probe shall be perpendicular to the radius of the measurement circle. For all

measurement setups, the measuring probe shall be connected to the common reference ground. Proximity effects caused by the observer and nearby objects should be made negligible (i.e., <1%). Properly routed the probe cable, checked background fields, noted temperature, and avoided placement of the probe in nonuniform fields to avoid measurement uncertainty. The calibration circuit and test setup is adhere to IEEE Std 1140 [43].

Magnetic Field Meter: The HIOKI FT3470-50 MAGNETIC FIELD HITESTER (Fig. 2.4) is used to measure magnetic flux density (Tesla or Wb/m^2) measurement. It operates between 10 Hz and 400 kHz in frequency. This meter complies with the ICNIRP 2010, IEC62110/IEEE 644, IEC 61786, as well as IEC 62233 guidelines for measuring instrument requirements. The FT3470-52 is a sensor that measures the true RMS value for all three axes (XYZ) simultaneously and calculates the composite (R) value. FT3470-52 sensor complies with the IEC/EN 62,233 standards. The sampling is set to a fixed interval of 10 s/div (about 4.4 h) in application software HIOKI DATA VIEWER, and the recorded data is transferred to a laptop via a USB Ver. 1.1. Calibration of magnetic field meter was done at the HIOKI service provider testing lab, as per the standard IEEE Std 644. Calibration of a magnetic field meter is typically carried out by placing the probe in a nearly uniform magnetic field of known strength and orientation. Such reference fields can be generated using coil arrangements of circular or rectangular shapes. During calibration, the probe is positioned at the center of a single loop, with its plane aligned to that of the loop. For a probe with a 10 cm diameter, the loop should measure at least $1 \text{ m} \times 1 \text{ m}$. The loop size can



Fig. 2.4. Magnetic field meter.

be adjusted proportionally for larger or smaller probes to ensure similar field uniformity across the probe. For three-axis probes, calibration must be conducted separately for each axis. It is important to note that nearby ferromagnetic materials may disturb the calibration field. Energizing power supplies used for calibrations shall be nearly free (<1%) of harmonic content. The magnetic field measurement procedure is simple and user-friendly, the values obtained using the FT3470-50 tester can be imported to a PC for graphic representation. The calibration circuit and test setup is adhere to IEEE Std 644 [44].

2.2. Measurement of Electric and Magnetic Fields in Electric Vehicles

Electric field intensity and magnetic flux density have been measured at four different vehicles named EV1, EV2, EV3, and EV4 in running condition. All considered EVs are plug-in BEVs and on-board charger type. Specifications of vehicle drive type, electric motor, electric power, energy density, and battery type for different EVs are given in Table 1. EV1 operates on a 400 V battery architecture with a nominal voltage of 332.8 V. It is adaptive to both AC (3.3 kW and 7.2 kW) and DC (50 kW) charging methods. EV2 has an 84 V battery architecture and 72 V nominal voltage system; it will adapt only to a 3.3 kW AC charger. EV3 utilizes a 400 V battery architecture, with a nominal voltage of 320 V, and is compatible with both AC and DC, like the EV1. EV4 uses an 800 V high-voltage battery system, and it operates at a nominal of 697 V. It will support AC home charging (7 kW and 11 kW) and a DC ultra-fast charger (350 kW).

The measurement positions inside EV were selected based on two concepts, such as positions nearer to power sources and considering biological effects to the organs, which are well defined by WHO and other scientific literature. Near the driver's leg is due to the factor of power flow between motor and driving mechanisms, such as speed, acceleration, and braking. The battery pack is housed within the chassis

Table 1
Specifications of measured EVs.

	Drive type	Electric motor	Electric power (kW)	Energy density (kWh)	Battery type
EV1	Front-wheel	AC PMSM	106	45	Lithium-ion
EV2	Rear-wheel	AC Induction motor	7.5	12	Lithium iron phosphate
EV3	Front-wheel	AC PMSM	95	30	Lithium-ion
EV4	Rear-wheel	AC PMSM	160	72.6	Lithium-ion

in the vicinity of rear seat. Power near dashboard influences field near torso and head of the driver. The biological effects are severe to organs near head, leg, and torso hence measured exposure near to driver and passenger. Proximity to different positions (Fig. 2.5), such as leg, torso, head, dashboard, rear seat, and chassis inside the vehicles, has been measured to observe electric and magnetic field exposure for the human external body. Pictures taken during measurement of the magnetic field (Fig. 2.6) at different positions, such as Fig. 6a-dashboard, Fig. 6b-driver head, and Fig. 6c-chassis while driving, are depicted. The measured E-field with respect to time of EV1 while driving in city mode is shown in Fig. 2.7. Fig. 2.8 is measured B-field with respect to time, where Fig. 2.8a is proximity to leg, 2.8b to torso, 2.8c to head, 2.8d to dashboard, 2.8e to rear seat and 2.8f to chassis. Similar fields have been observed for EV2, EV3, and EV4. The maximum recorded magnitudes of E and B for all considered EVs at different positions are tabulated with their corresponding ambient atmospheric conditions in that location are mentioned in Table 2.

2.3. Measurement of Electric and Magnetic Fields in EVSEs

In this section, four different EVSEs (named EVSE1, EVSE2, EVSE3, and EVSE4) are taken for E and B exposure analysis during charging conditions. EVSE1 is a level 2 domestic-type AC wall-mounted charger in an apartment car park. EVSE2 is a level 1 AC charger. EVSE3 is a level 2 solar-powered hybrid charging station located in a university. EVSE 4 is a level 3 public fast charger installed along Bangalore-Chennai highway roads. Table 3 gives specifications of charger type, voltage type, rated power, maximum output current, output voltage, and charging time for considered EVSEs. The charging time represented is for 10 % to 100 % State of Charge (SoC).

Measurements have been taken for proximity to connector, battery, at 10 cm and 60 cm distances away from the charger of all EVSEs. The different measurement positions are marked in Fig. 2.9. Fig. 2.10 showcases pictures taken during measurement of the electric field at different positions, such as Fig. 2.10a-AC charger, Fig. 2.10b-battery, and Fig. 2.10c-connector while charging. The measured E-field with respect to time for EVSE1 is plotted in Fig. 2.11. Fig. 2.12 is the measured B-field with respect to time, where Fig. 2.12a is proximity to connector, 2.12b to battery, 2.12c to charger at 10cm and 2.12d to charger at 60 cm. Similar fields have been observed for other three chargers at same proximities. The maximum recorded magnitudes of E and B for all considered EVSEs at different positions with their corresponding SoC are tabulated in Table 4. Ambient atmospheric conditions in those locations are also included in Table 4.

3. Electromagnetic Field Computational Analysis

This section presents the computational analysis of electric and magnetic field distribution around an electric vehicle AC charging cable. Preliminary simulation work is carried out to compare the measured

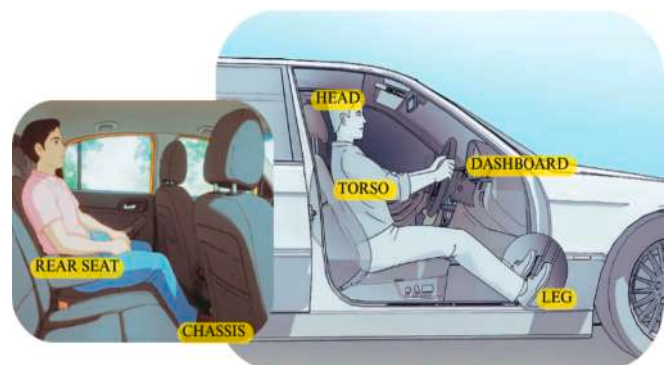


Fig. 2.5. Different positions inside EV for E and B measurements.



Fig. 2.6. Pictures taken during B field measurement at different positions while driving.

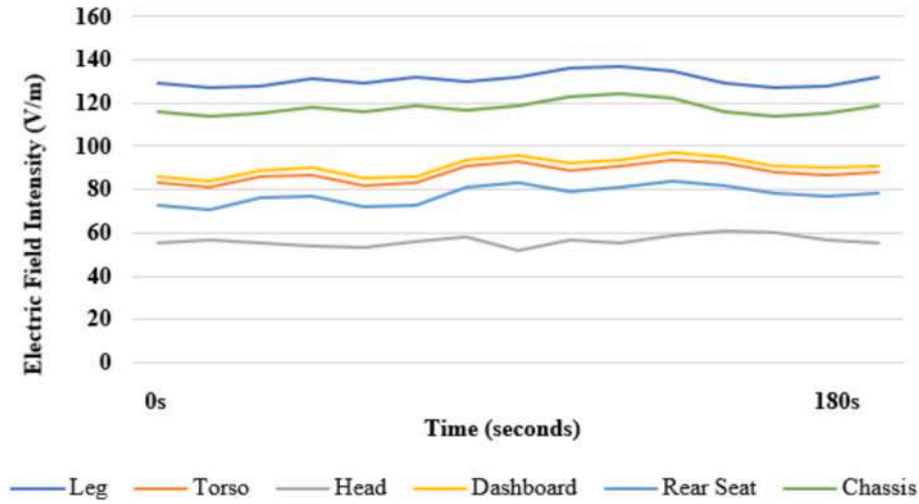


Fig. 2.7. Electric field intensity at different positions inside EV1 while driving.

results with AC charging cable, where field strength is relatively high. The analysis is performed using COMSOL Multiphysics® software, a versatile numerical tool for solving electromagnetic field problems. The finite element method is employed for numerical modelling. The field distribution is examined based on the actual geometry of an electric vehicle IEC Type1 AC charging cable.

3.1. Modeling Configuration

The configuration used here is the typical dimension of EVSE1, domestic wall-mounted 7.5 kW AC charger specified in section II above. The modelled EV charging cable core and insulation layers is shown in Fig. 3.1, as per the standard EN50620. The dimension of cable structure is $3 \times 6.0 \text{ mm}^2 + 2 \times 0.5 \text{ mm}^2$ core area and 12.8 mm outer diameter [45]. The terminal/phase voltage of 265 V AC, 50 Hz 1 ϕ supply, maximum current of 32 A, neutral-to-ground voltage of 2.5 V, ground voltage (0 V), and control pilot and proximity pilot signals of 6 V are considered as input for cable core. Fig. 3.2 shown below is a three-dimensional geometric tetrahedral mesh model under air boundary condition. Predefined mesh refinement is kept in extra fine mode. Solution time took to run this simulation was 32 min, 31 s in 64-bit operating system with an x64-based processor, 16.0 GB RAM with speed of 1.70 GHz. The material properties such as conductivity, relative permittivity and permeability are given in Table 5. A detailed description about the solver, governing equation, boundary and field

distribution plots are explained further.

3.2. Electric Field Intensity Analysis

The electric field distribution in cable geometry is analyzed using Electric Currents (ec) solver under AC/DC module of COMSOL Multiphysics. The governing equations used for FEM based electromagnetic field computation are fundamental laws of electromagnetism, particularly Maxwell's equations and Ohm's law in differential form.

$$\nabla \cdot \mathbf{J} = \mathbf{Q}_j, \mathbf{v}.$$

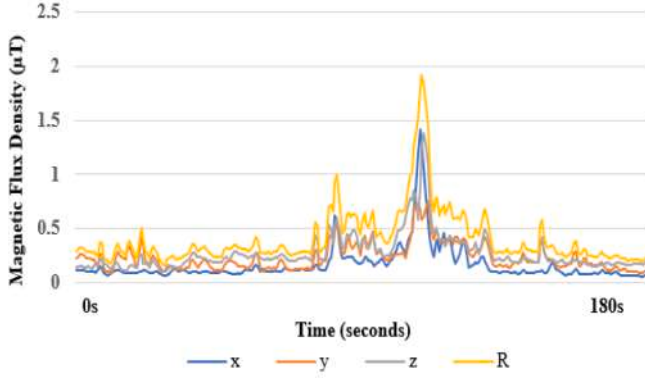
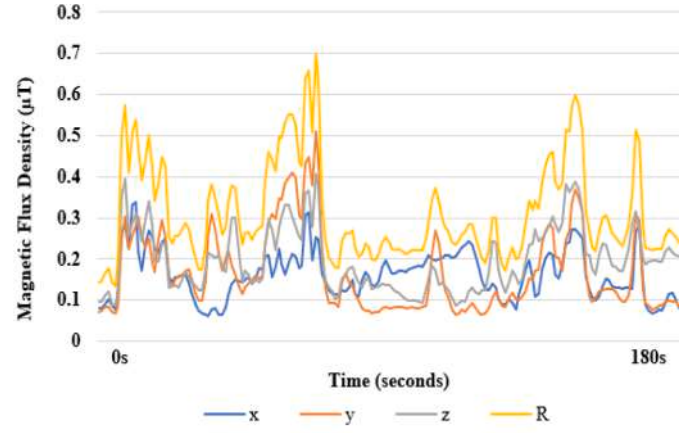
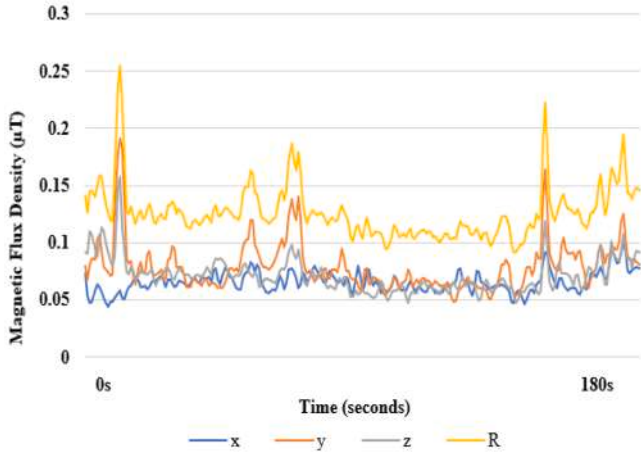
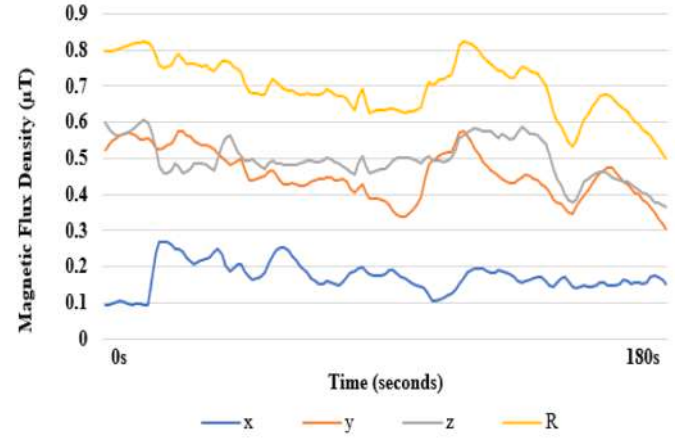
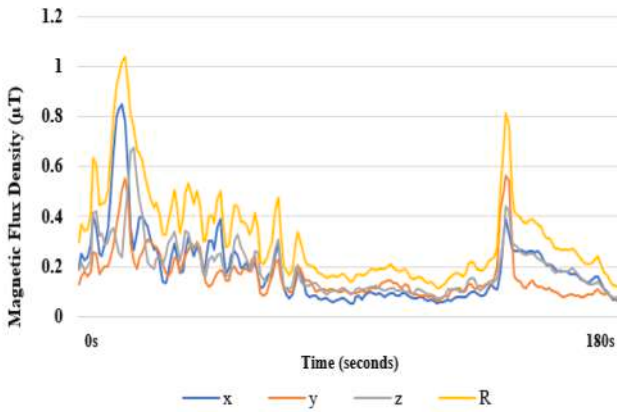
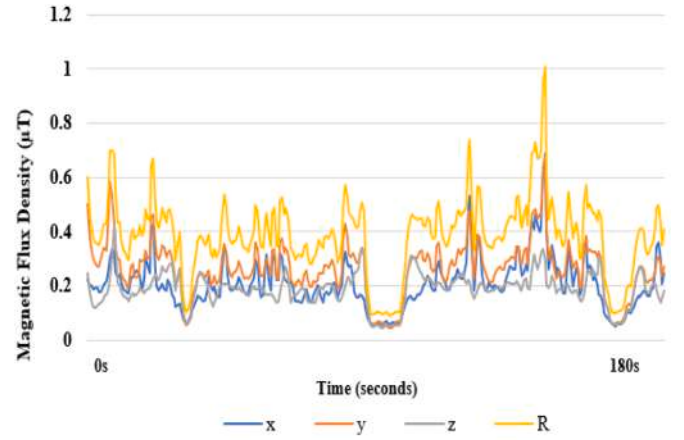
$$\mathbf{J} = \sigma \mathbf{E} + \mathbf{j} \omega \mathbf{D} + \mathbf{J}_e.$$

$$\mathbf{E} = -\nabla V.$$

where $\mathbf{D} = \epsilon \mathbf{E}$, $\mathbf{J}$ = current density, $\mathbf{Q}_j, \mathbf{v}$ = current source density (charge conservation term), σ = electrical conductivity, $\mathbf{E}$ = electric field intensity, ω = angular frequency, $\mathbf{D}$ = electric flux density, $\mathbf{J}_e$ = external current density, V = electric potential.

Fig. 3.3 shows the potential distribution plot of electric vehicle AC charging cable structure from conductor core to outer sheath. The legend from red to purple color represents higher to lower voltage level, i.e., 265 V to 0 V. Contour plot is shown in Fig. 3.4, where equipotential lines are scaled linearly from the outer surface of conductor to the sheath. It can be inferred that the potential strength is higher and denser near the outer surface of conductor and decreases when distance increases from conductor surface.

The magnitude of electric field intensity along cable radial direction

**a. Proximity to Leg****b. Proximity to Torso****c. Proximity to Head****d. Proximity to Dashboard****e. Proximity to Rear Seat****f. Proximity to Chassis****Fig. 2.8.** Magnetic flux density at different positions inside EV1 while driving.

of phase and neutral conductor is shown in Fig. 3.5. Field inside the conductors is 'zero' which is pointed out in the line graph. Maximum of 229 kV/m is absorbed at the center of cable which then decreases exponentially from the outer surface of conductor. This behavior follows the fundamental cable relation, $E \propto V/r$. E-field is directly proportional to voltage; hence, it is higher around the phase conductor than the neutral conductor. The field strength decreases when distance increases

from the cable conductors, which is inversely proportional to distance. The elevated E-field spikes noted in the graph are due to relative permittivity ϵ_r of cable insulation materials, which is inversely proportional to electric field intensity. E-field value from cable outer surface i. e., charger at 10 cm is mentioned in the line graph of Fig. 3.5a with a zoom-in view. The noted E-field value is 832 V/m for charger at 10 cm.

Table 2

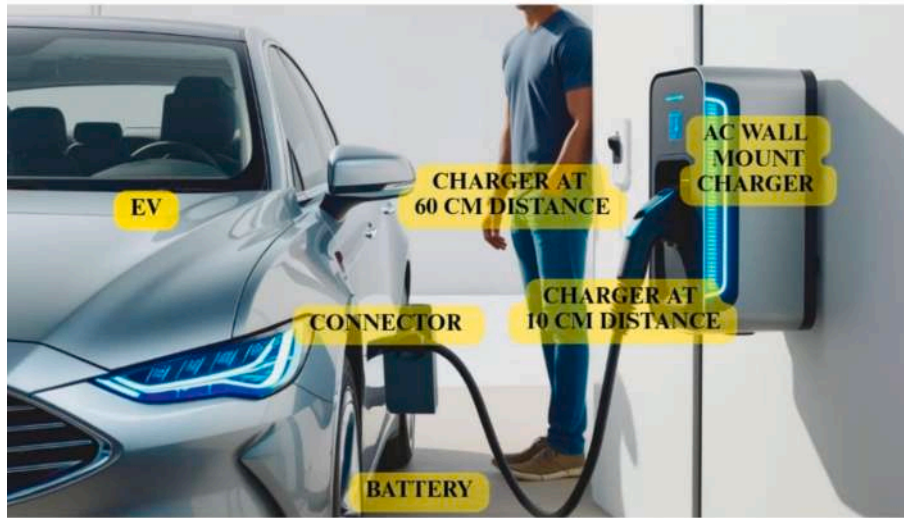
Maximum E and B for different EVs at different positions while driving.

	Ambient Atmospheric Conditions			Leg		Torso		Head		Dashboard		Rear Seat		Chassis	
	T (C)	P (mbar)	H (%)	E (V/m)	B (μT)	E (V/m)	B (μT)	E (V/m)	B (μT)	E (V/m)	B (μT)	E (V/m)	B (μT)	E (V/m)	B (μT)
EV1	28	1012	84	137	1.92	94	0.67	61	0.25	97	0.81	84	1.1	124	1.0
EV2	31	1011	59	57	0.85	64	1.56	36	0.8	69	1.6	67	0.28	64	0.88
EV3	29	1010	74	97	1.75	60	0.78	40	0.2	76	0.7	62	0.95	79	0.86
EV4	32	1005	71	49	0.98	53	0.9	30	0.67	26	0.56	19	0.4	33	0.89

Table 3

Specifications of measured EVSEs.

	Charger Type	Voltage Type	Rated Power (kW)	Maximum Output Current (A)	Output Voltage (V)	Charging Time
EVSE1	DomesticWall Mount	AC	7.5	32	90-265	6 h 36 min
EVSE2	DomesticWall Mount	AC	3.3	13	230	13 h
EVSE3	Workplace	AC	7.5	30	110-220	8 h
EVSE4	Public Fast Charger	DC	240	250	200~750	18 min

**Fig. 2.9.** Measurement positions in EVSE while charging.

3.3. Magnetic flux Density Analysis

The magnetic field distribution in EV charging cable is analyzed using Magnetic Fields (mf) solver under AC/DC module of COMSOL Multiphysics. The governing equations describing the magnetic field formulation commonly used in low-frequency electromagnetic simulations are

$$\nabla \times \mathbf{H} = \mathbf{J}.$$

$$\mathbf{B} = \nabla \times \mathbf{A}.$$

$$\mathbf{J} = \sigma \mathbf{E} + \mathbf{J}_e.$$

where $\mathbf{B} = \mu_0 \mu_r \mathbf{H}$, $\mathbf{J} = \sigma \mathbf{E}$, $\mathbf{H}$ -magnetic field intensity, $\mathbf{J}$ -current density, $\mathbf{B}$ -magnetic flux density, $\mathbf{A}$ -magnetic vector potential, σ -electrical conductivity, $\mathbf{E}$ -electric field, $\mathbf{J}_e$ -externally applied current density. These equations describe the magnetic field behaviour in a conducting region.

The input current given to the phase conductor is 32 A and -32 A to neutral conductor. In a current-carrying conductor, the magnetic field lines form circles around it, which can be seen in Fig. 3.6. The curl of a magnetic field measures its localized circulation or swirling effect, and it is mathematically defined by Ampere's Law. Also, the curl of magnetic field is related to the magnitude and direction of this circular motion. Comparing to negative/neutral conductor, flux lines are highly clustered

around positive phase conductor and it decreases when distance increases, as shown in Fig. 3.7.

The magnitude of magnetic flux density along cable radial direction of phase and neutral conductor is shown in Fig. 3.8. Maximum of 5.48 mT is absorbed on the surface of phase conductor, then it decreases when distance increases. At the center of cable, B-field dipped which is pointed out in Fig. 3.8, in-between two opposite current-carrying conductors. This is due to flux lines follow the fundamental law of 'Right hand thumb rule', where flux lines cancel each other. The B-field value from the cable outer surface i.e., charger at 10 cm is mentioned in the line graph of Fig. 3.8a with a zoom-in view. The noted B-field value is 132 μT for charger at 10 cm. Similarly, for EVSE3 the simulated values are given in comparison Table 7. EVSE1 and EVSE3 are chosen for simulation comparison, due to the current rating and dimension of cable geometry are almost similar. Further in section IV, simulated E-field and B-field magnitudes are compared with measurement values at the same position of 10 cm mentioned in section II above to validate the measured readings of EVSE1 and EVSE3.

4. Results

This section describes the measurement results for the various

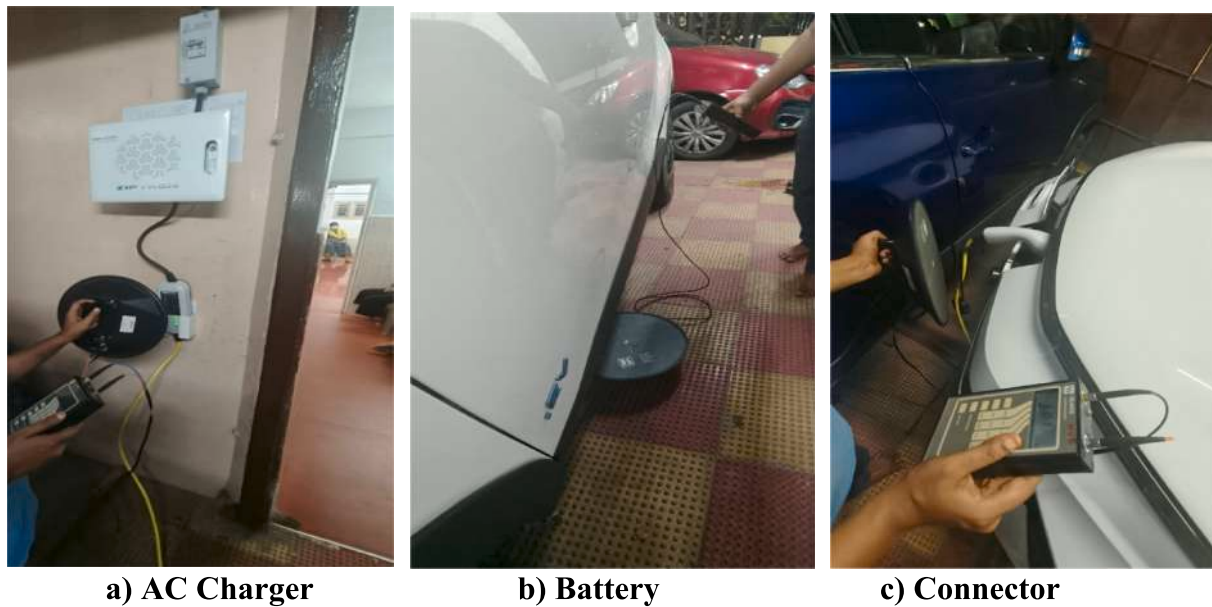


Fig. 2.10. Pictures taken during E field measurement at different positions while charging.

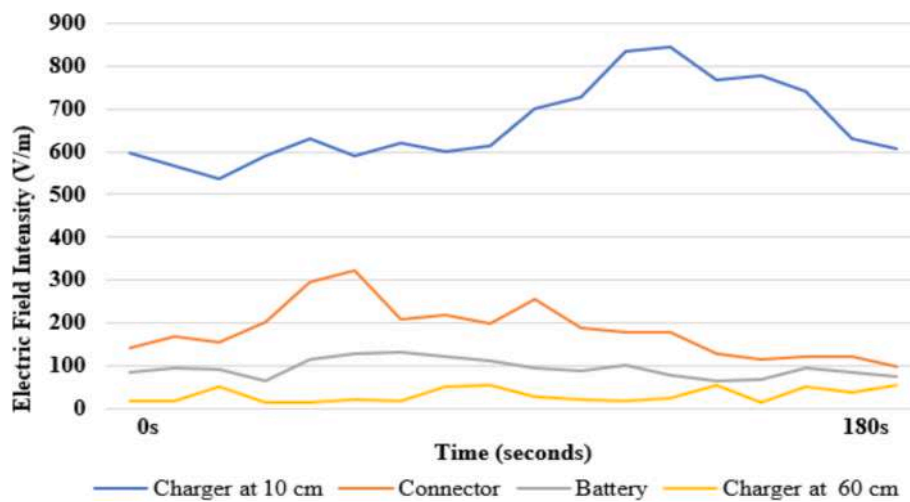


Fig. 2.11. Electric field intensity at different positions in EVSE1 while charging.

electric vehicles and electric vehicle supply equipment that are considered in this work. Additionally, computational results from the finite element model of electric vehicle AC charging cable are compared with measurement results.

4.1. Measurement Evaluation

Measurement were done in and around Chennai city at various location where corresponding atmospheric conditions such as temperature, pressure, and humidity were recorded prior to each measurement. As per standard IS2071, ADCF (Air Density Correction Factor) in this location is 1. Hence, no correction factor was applied. Summary of measured electric and magnetic field values of EVs and EVSEs is included in Table 6; observed values at each point are compared with standard exposure limits of general public guidelines. Compared with ICNIRP 2010 magnetic flux density to the general public outer body exposure limit (200 μ T), the IEEE limit (904 μ T) is less restrictive, reflecting different safety factors and assessment methods. In IEEE C95.1 the given magnetic field reference level to head, torso and leg is less restrictive. But the electric field reference level is same as ICNIRP.

The maximum magnitude of E for different EVs at different measured positions inside the EV is compared in Fig. 4.1. The inferences observed are mentioned below.

- The observed electric fields are greater in the order of EV1 > EV3 > EV2 > EV4 in leg, head, dashboard, and chassis positions. But in torso and rear seat EV1 > EV2 > EV3 > EV4; this might be due to the battery arrangements of EV2 and EV3.
- The electric fields in EV1, when compared with different positions from Fig. 6, are leg > chassis > dashboard > torso > rear seat > head.
- Even though EV4 has a higher power rating, it has a lower electric field when compared with other considered EVs at all positions due to the well-designed vehicle configuration. EV4 is another fast-moving market share next to EV1 and EV3. When compared to other three EVs, this is high-end model, fully automated. The length and width of EV4 are bigger (4715 x 1940 mm), which is higher than EV1 (3995 x 1802 mm) and EV3 (3995 x 1804 mm).
- The placement of power sources such as battery, motor, dashboard and other power cables is well arranged, which as adequate clearance from sources inside the vehicle. In general, electric field

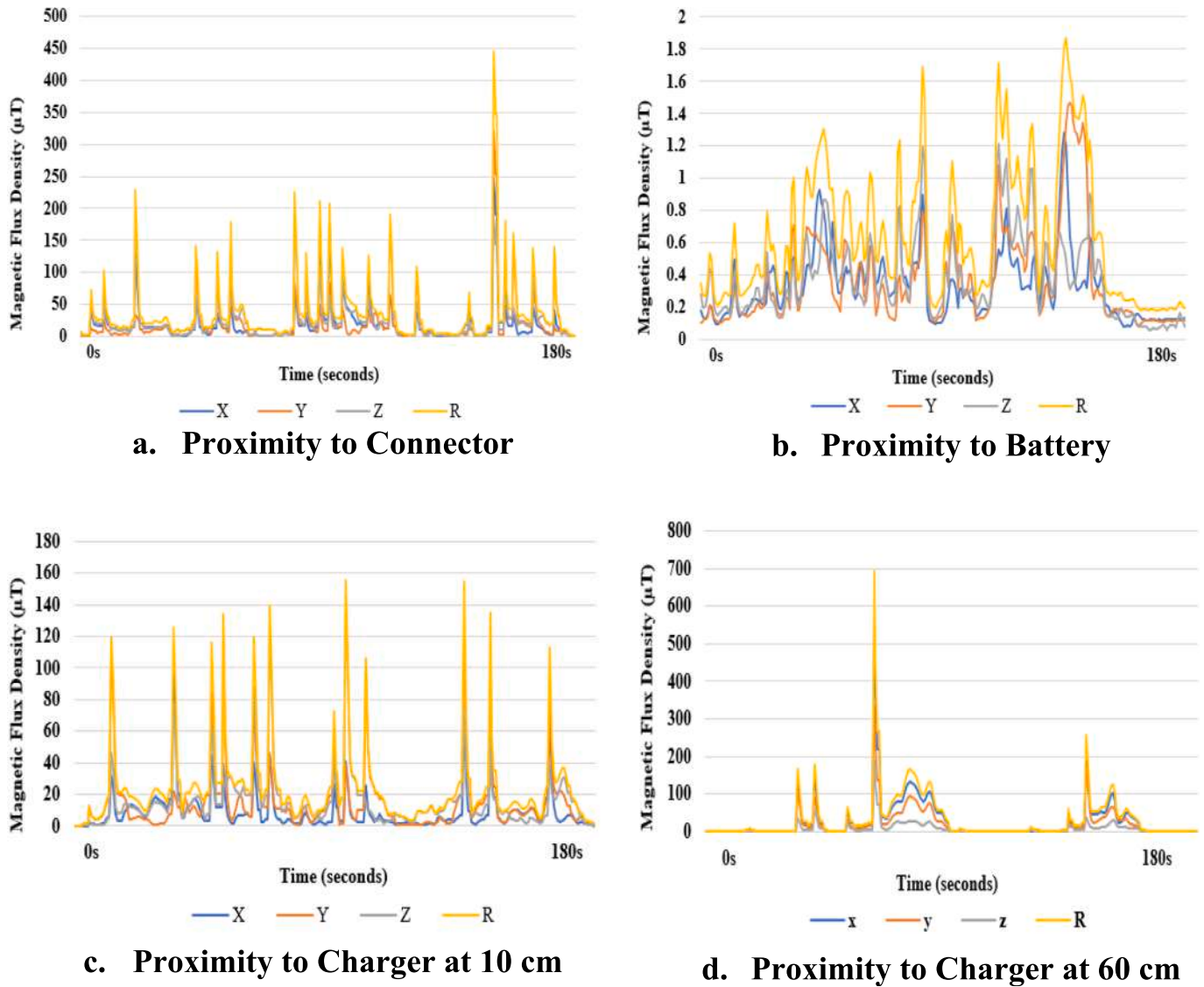


Fig. 2.12. Magnetic flux density at different positions in EVSE1 While Charging.

Table 4
E & B at different positions while charging.

	Ambient Atmospheric Conditions			Connector		Battery		Charger at 10 cm		Charger at 60 cm		SoC (%)
	T(C)	P (mbar)	H(%)	E (V/m)	B (μT)	E (V/m)	B (μT)	E (V/m)	B (μT)	E (V/m)	B (μT)	
EVSE1	28	1012	84	321	445.1	132	1.86	845	155.2	56	692.9	70
EVSE2	35	1005	57	197	62.04	100	20.44	375	80.74	33	0.66	83
EVSE3	31	1012	59	294	73.43	126	52.38	596	124.3	26	21.17	78
EVSE4	33	1017	51	22	54.26	18	59.5	24	88.3	16	0.17	50

intensity E is directly proportional to voltage and inversely proportional to distance, which decreases when distance or clearance increases. Similarly, magnetic flux density decreases when distance increases.

- Amongst different measured positions inside EVs, the maximum electric field intensities observed are in proximity to the leg and torso due to the factor of power consumption during driving mechanisms, such as speed, acceleration, and braking. Also, near the chassis, the placement of the battery influenced the electric fields in all EVs.
- The dashboard, torso, and rear seat are almost equal in electric fields in all four EVs. In addition, electric field is significantly lower near

the head of a driver compared to other positions, as the E field would reduce when distance increases from the source.

The maximum magnitude of B for different EVs is compared in Fig. 4.2 with different measured positions inside the EV. The inferences obtained are given below.

- Regarding the magnetic field density among different considered EVs, EV1's is greater near leg, rear seat, and chassis positions. Then EV2's is greater near the torso, dashboard, and head. Following that, EV3 and EV4 shared almost second of all positions.

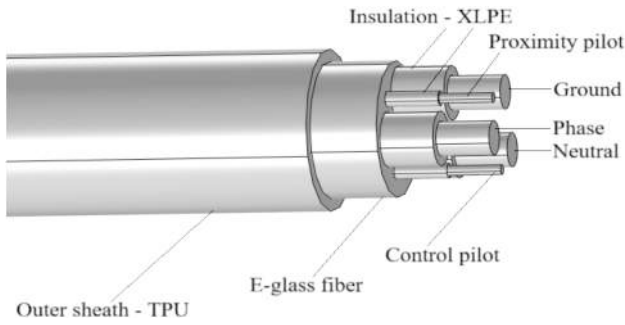


Fig. 3.1. Electric Vehicle AC Charging Cable Structure.

- Primarily, the observed B is higher near the leg of a driver for EV1, EV3, and EV4 and the dashboard for EV2. This might be due to high power flow during running condition.
- The proximity of B to the chassis is approximately 1 μT in all EVs. Furthermore, observed B near the head is very less because of the distance apart from current sources.

With reference to Fig. 4.3, the maximum magnitude of E for different EVSEs at different measured positions during charging is compared.

- The observed electric fields are $\text{EVSE1} > \text{EVSE3} > \text{EVSE2} > \text{EVSE4}$ in proximity to the connector, battery, 10 cm and 60 cm distance away from the charger.
- At the same time, the electric field in EVSEs among four different positions the charger at 10 cm > connector > battery > charger at 60 cm.
- Significantly, the electric field is much less near the battery and at 60 cm away from the charger, which is negligible.

The maximum magnitude of B at different measured positions during charging for different EVSEs is compared in Fig. 4.4.

- The magnetic field is greater in the order of $\text{EVSE1} > \text{EVSE3} > \text{EVSE2} > \text{EVSE4}$ near the connector, 10 cm and 60 cm distance away from the charger. But, near battery in the order of $\text{EVSE4} > \text{EVSE3} > \text{EVSE2} > \text{EVSE1}$.
- Further, the magnetic fields in EVSEs are observed among four different positions, charger at 10 cm > connector > battery > charger at 60 cm.
- At the same time, B for EVSE1 is comparatively much high than other EVSEs, around 445.1 μT near the connector, 155.2 μT at 10 cm away from the charger, and noted a maximum magnitude of 692.9 μT at 60 cm away from charger. Also, near charger at 10 cm for EVSE3 is 124.3 μT .
- The magnetic flux density in two positions of EVSE1 exceeded standard guidelines for exposure limits to humans' external body (>200 μT) (Fig. 2.1b and Fig. 2.2).

- The high magnetic field observed in EVSE1 (installed in the apartment parking area) might be due to electromagnetic interference environments, such as household water pumps and AC cables. The spotted picture is shown in Fig. 4.5.
- This high-power electrical equipment might cause interference to the nearby EVSEs. Hence, installing chargers with clearance from other electrical sources is necessary to avoid E and B fields and their interferences. To avoid EMF radiation near charger and connector a proper shielding and grounding must be employed within power components and cables of EVSE.
- Measured E and B fields in EVSE4 DC fast charger are very much less than other AC charging units due to non-time-varying voltage and current.

4.2. Comparison of Measurement with Computational Results

The position at 10 cm away from charger is rely on input power supply. Hence, this computational analysis is done only with the cable as a preliminary work. The simulated values at 10 cm distance from AC charging cable, the electric field intensity and magnetic flux density were matched closely with the measurement values. Comparison of computational values of EVSE1 and EVSE3 with measurement values, including percentage deviation are given in Table 7 for 10 cm position. The measured values are higher than the computed values, likely because the measuring instruments also detected electromagnetic emission from other sources within the EVSE and EV systems. Further, for other measurement positions in EVSE (Fig. 2.9), simulation work has to be done in future, considering a real geometry of an on-board vehicle, which consists of built in AC-to-DC rectifier, battery, cable with connector, and other power sources, including a human standing next to the vehicle.

5. Discussions

To cater to the growing demand for fast charging in commercial

Table 5
Material dielectric properties.

Materials	Objects	Electrical Conductivity σ (S/m)	Relative Permittivity ϵ_r (F/m)	Relative Permeability μ_r (H/m)
Copper	Cable Core/Conductor	5.99×10^7	1	1
Cross-linked Polyethylene (XLPE)	Cable Insulation	1×10^{-18}	2.5	1
E-glass fibre	Inner sheath	1×10^{-22}	5	1
Thermoplastic polyurethane (TPU)	Outer sheath	1×10^{-15}	4.4	1
Air	Boundary	1×10^{-14}	1	1

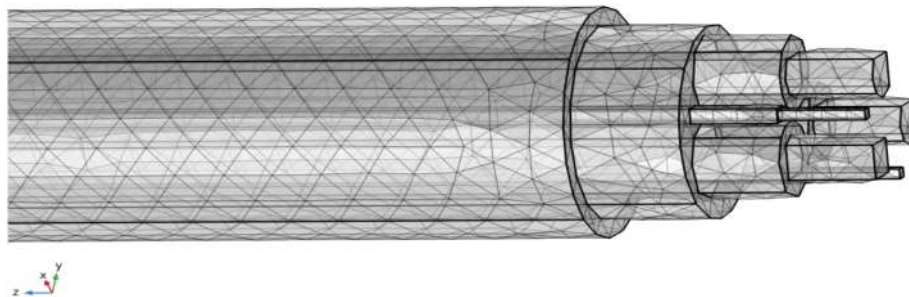


Fig. 3.2. Three-dimensional geometric tetrahedral mesh model.

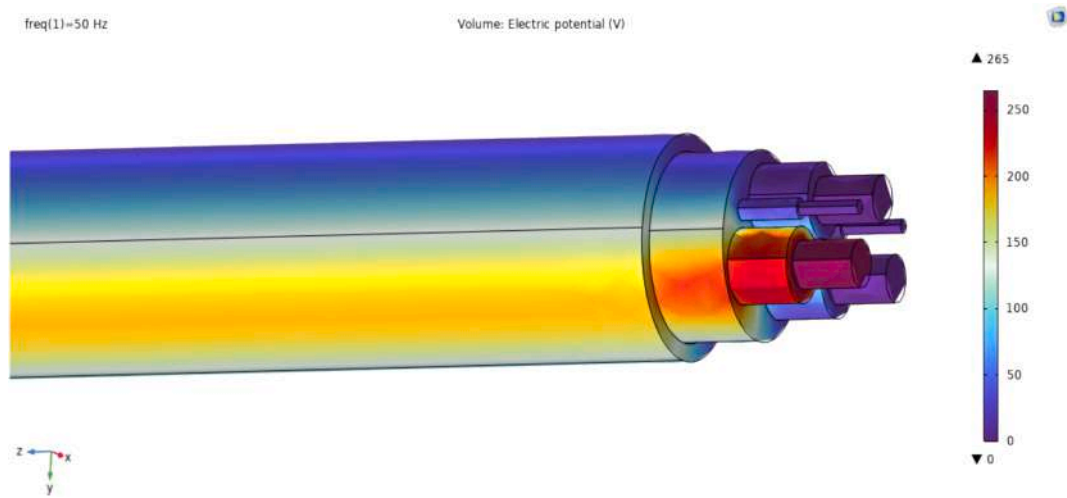


Fig. 3.3. Electric potential distribution plot of charging cable.

areas, especially on the highways, well-infrastructure supercharging zones with capacities of 360 kW and 240 kW DC have been launched throughout the nation since 2023. The station includes a dedicated EV tariff distribution power line laid by the electricity government. Following that, Ac-to-DC converter is installed and linked to a common DC bus where all EVSE taps DC voltage for recharging. During measurements at above said public fast charging stations, we noticed that while charging, most of the people were not stepping out of the vehicle. They were comfortably sitting inside the vehicle with air conditioning to avoid outside heatwaves (why because South India is generally hotter and more tropical), specifically when they were supposed to take a long travel. The workers handled plugging in and unplugging the charging

cables, then they stood near the chargers until the vehicle got charged. On the other hand, we witnessed that many domestic chargers have been installed close to ground-floor living places and close to other electric equipment without clearance. Space scarcity was a bigger issue in high-density populated urban cities for installing domestic EV chargers with clearance from the living area. Henceforth, the study of electromagnetic field distribution in EVs and EVSEs is necessary to analyze emission levels.

Research articles have addressed the importance of continuous monitoring of low-frequency electromagnetic field exposure from electric and hybrid vehicles to mitigate health and safety risks. EMF exposure levels can vary depending on the specific EV design, component location, and

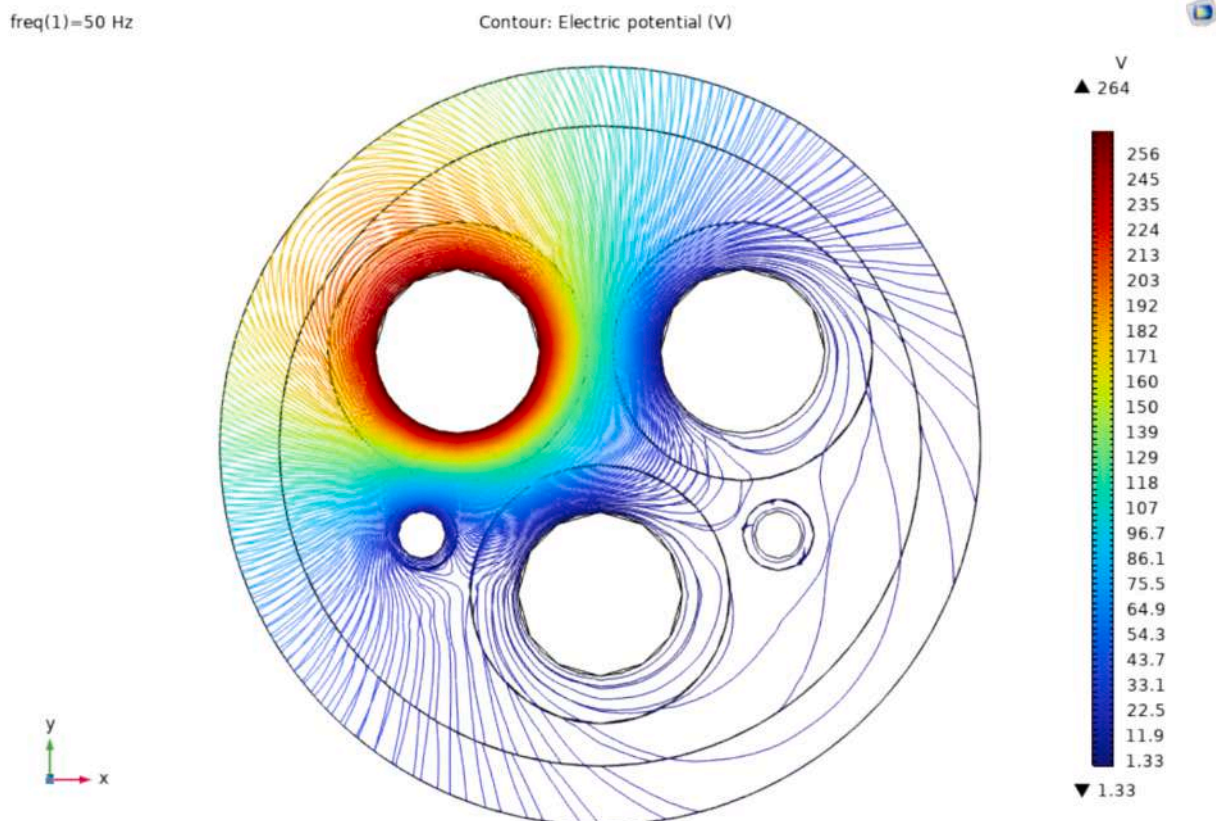


Fig. 3.4. Equipotential plot of charging cable.

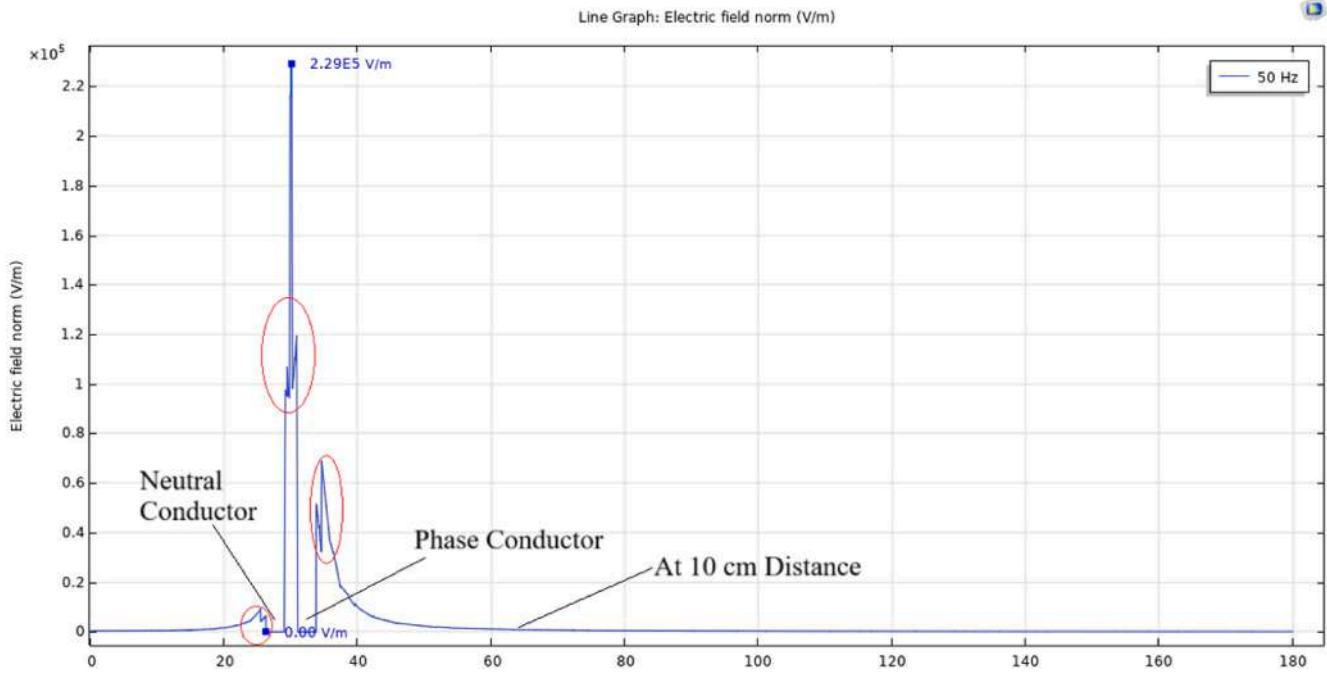


Fig. 3.5. Electric field intensity – line graph along cable radial direction.

proximity to the EMF sources. Passengers and drivers are exposed to a complex mix of ELF and Radio Frequency (RF) EMF from internal and external sources. EVs produce EMFs across a broad spectrum, from 0 Hz when stationary up to approximately 1 MHz. The driving systems generate dominant ELF components; wireless communication systems inside and outside the vehicle produce RF components. Concerns exist regarding the safety of individuals with medical devices, such as cardiac pacemakers, due to potential electromagnetic interference from EVs [46]. Summarized available results of magnetic surveys taken in a variety of electrically powered transportation systems, with the focus on automotive exposures. Maximum automotive magnetic field magnitudes in different studies varied from a few units of μT to $120 \mu\text{T}$ [47]. The study measured magnetic flux density in three shared electric vehicles,

recording data at front and rear seats during different driving modes, such as acceleration and constant speed. A significant finding was that replacing vehicle components alters the magnetic field amplitudes. The research noted that regular maintenance did not influence the magnetic field values, but major repairs or modifications had a noticeable impact. The study emphasized the necessity of regularly monitoring ELF magnetic fields in EVs, particularly after significant maintenance, accidents, or replacement of components [48]. Magnetic field measurements in electric vehicles are carried out to evaluate human exposure to low-frequency fields. These measurements are typically performed in various parts of the vehicle, such as the passenger cabin and areas surrounding the battery, using probes to detect peak exposure levels. Although elevated magnetic field values are often recorded near

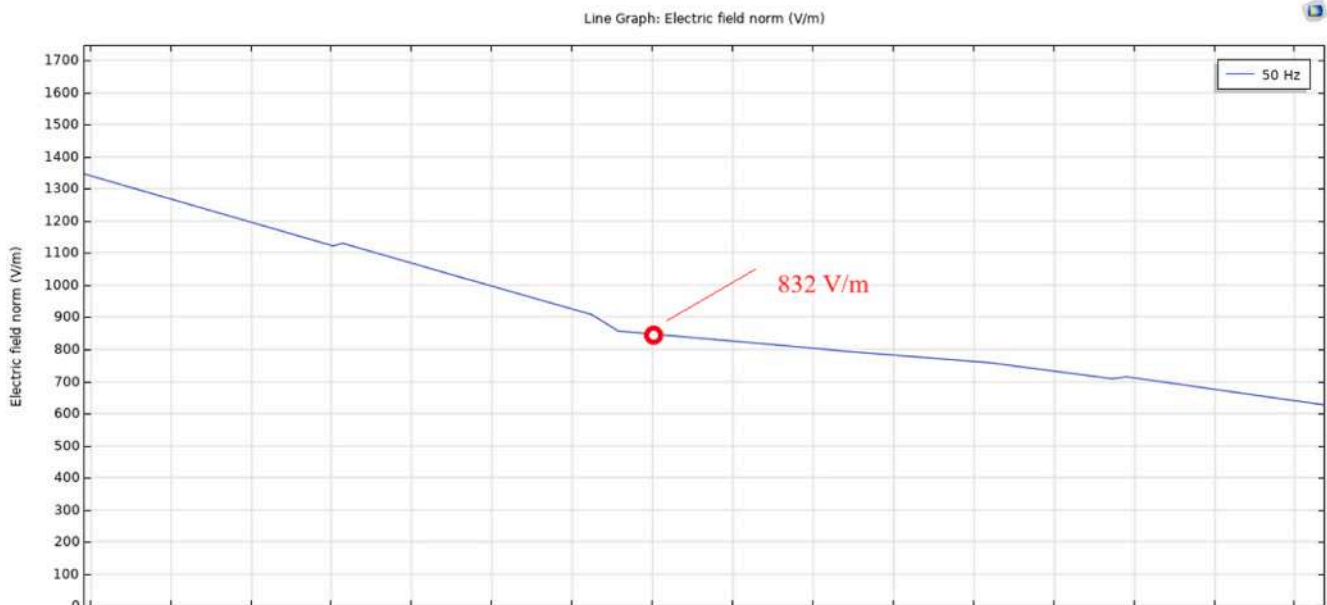


Fig. 3.5a. Electric field intensity at 10 cm distance away from charging cable – zoom-in view.

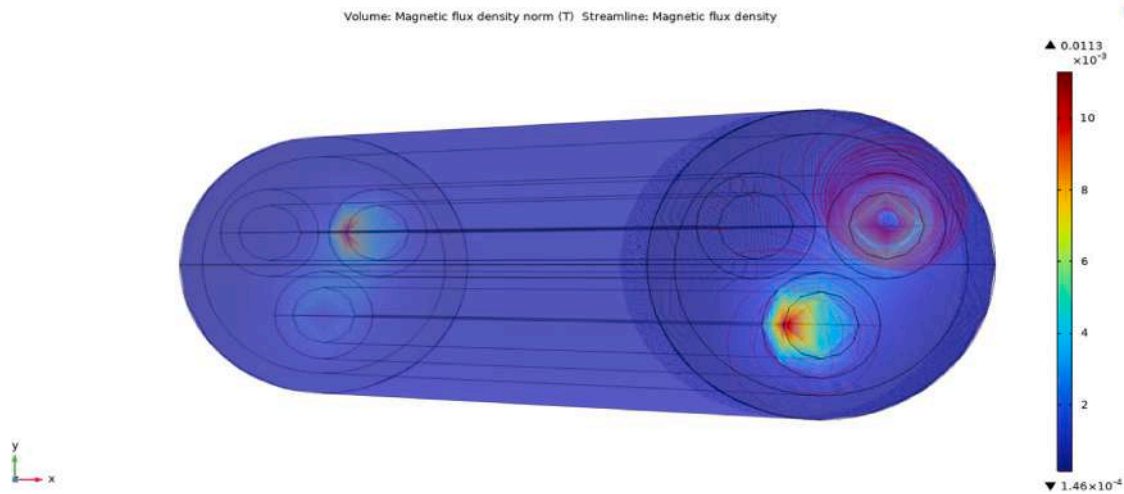


Fig. 3.6. Magnetic flux density plot of charging cable.

electrical components, the overall exposure levels generally remain well below internationally established health limits [49]. EVs produce higher low-frequency EMFs from batteries, drive trains, and cables, but these are non-ionizing and remain below international safety limits. Classic internal combustion engine vehicles emit much lower levels, while hybrids fall in between. Overall, EV EMF exposure is within safety standards, though design refinements can further reduce it [50]. Electromagnetic fields at EV charging stations are measured and compared with ICNIRP and IEEE standards. While exposure levels usually remain within limits, they depend on charger type, power, proximity, state of charge, and equipment design, with higher fields often occurring at higher charging powers [51]. Fully EVs exhibit higher low-frequency magnetic fields than conventional vehicles because of high-power components like inverters and DC busbars. Although levels may rise during acceleration or near the inverter, they usually remain within ICNIRP limits. Still, the emissions highlight the need for specific design and testing standards, especially to protect users with medical implants [52]. Literature shows the intense health effects of potential EMF exposure from other power sources in living areas. The potential electric

currents to be induced in bone marrow or other tissues exist if power lines come into contact with residential water distribution pipes [53,54]. Non-ionizing electromagnetic fields have effects on animal cells. It triggers neurodegenerative diseases and associated symptoms, such as headaches, sleep disturbances, and fatigue [55]. Also, no increased risk for acoustic neuroma has been found in a case-control study on occupational exposure to extremely low-frequency electromagnetic fields [56]. From a longitudinal cohort study, residential proximity to transformer stations and exposure to electromagnetic fields are linked to a borderline risk of pediatric cancer [57]. There is no evidence of a link between long-term electromagnetic radiation generated by the mobile communications system use and increased risk of cancer, based on the results [58]. The results of the current scientific research on the impact of EMF on human health are uncertain and recommend further, more comprehensive research. Hence, whilst designing EVs and EVSEs, the hazards of electromagnetic field emission and interferences must be taken into account to produce a validated electromagnetic compatible automotive.

Electric vehicle adoption increases worldwide hence, analysis of EMF

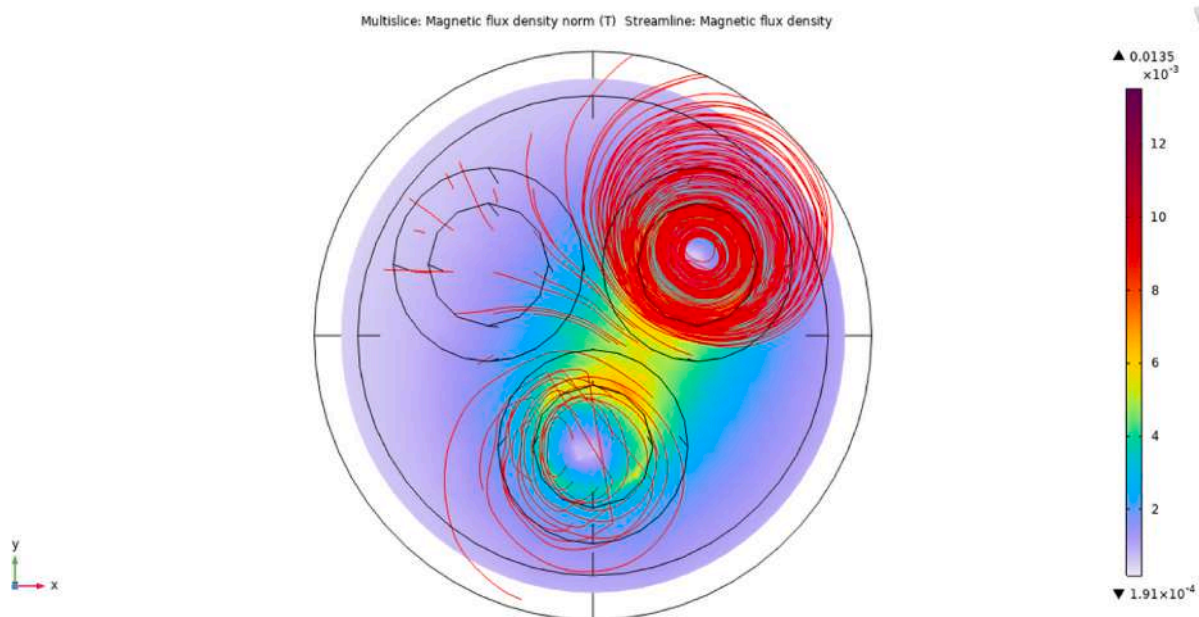


Fig. 3.7. Magnetic flux density streamlines inside the charging cable.

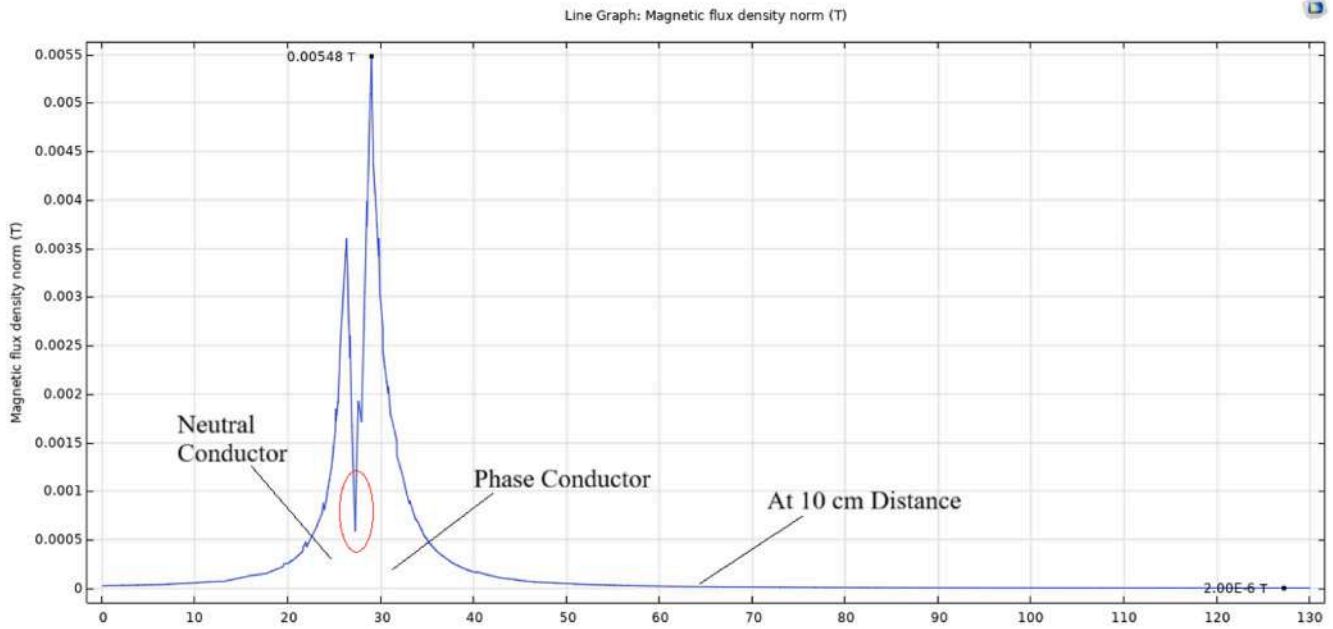


Fig. 3.8. Magnetic flux density – line graph along cable radial direction.

radiation levels in a wide range of EVs and EVSEs is important. Even though all vehicles are tested as per standards and coming to the market, many health issues are arising in practical cases due to EMF. Which necessitates a deeper study into the biological effects of long-term exposure of humans to EMF in the future. To find the internal body exposure level for different organs and its effect, an experimental study on the adult mice/rats has to be done for a long term. This kind of research was published by many authors for different biological cases and the results obtained from all the literature are used to frame regulations and standards by ICNIRP, WHO, IEEE, IARC, etc. for public and occupational exposure limit.

In spite of many other areas of research in e-mobility, such as improvement of battery technology for longer range, fast charging, battery capacity, range anxiety, charging infrastructure, etc. not much

work has been reported on the effect of EMF in EVs. Hence, this work is a novel approach to analyze a real-time EMF exposure to human while using e-mobilities in practice. The findings will create awareness among passengers and drivers about EMF exposure limits to them, and to monitor corresponding biological consequences. Including establishing a rigorous design technique to achieve e-mobility with electromagnetic compatibility by manufacturers. EV manufacturers must adhere to IEC standards for designing and EMC testing before it is put into the market. To minimize EMF exposure, it is essential that the design strictly comply with IEC 61851–21-1 standards on Electromagnetic Compatibility for on-board chargers and IEC 61851–21-2 standards on EMC for off-board chargers. The purpose is to ensure that the charger does not generate excessive electromagnetic interference that could disrupt other electrical systems and that the charger itself is not susceptible to EMI from

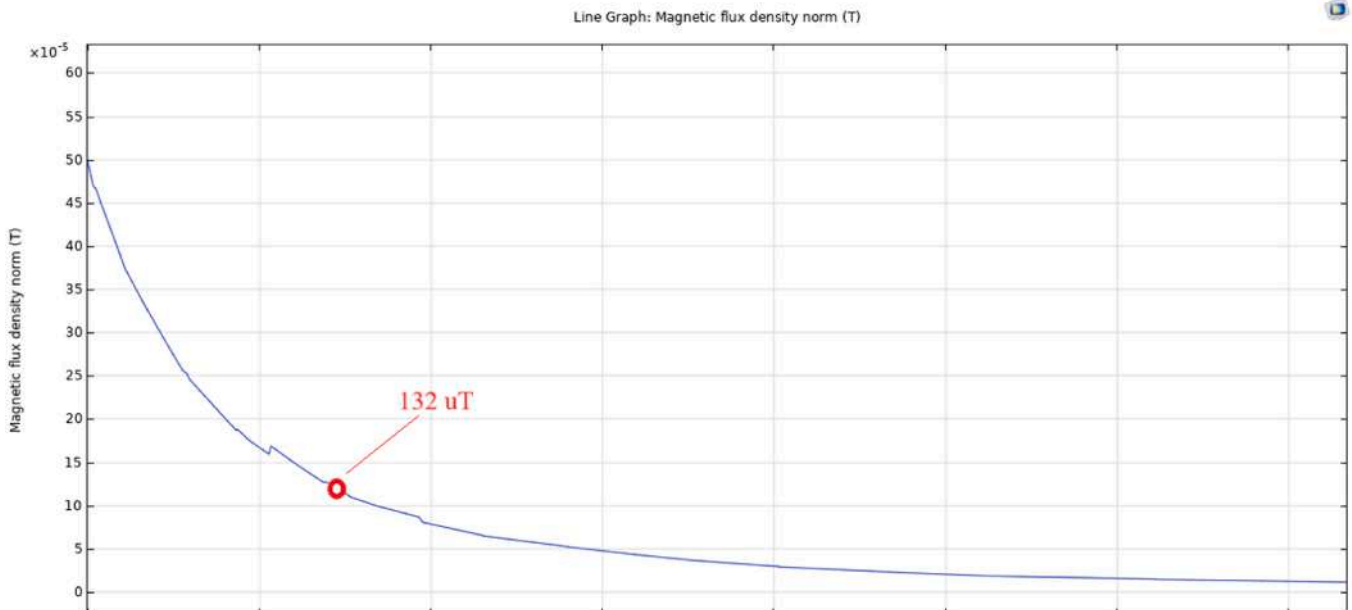


Fig. 3.8a. Magnetic flux density at 10 cm away from charger– zoom in view.

Table 6
Summary of Measured E & B Values of EVs and EVSEs.

ELF-EMF Guidelines for General Public – Electric and Magnetic Field Exposure Limits to Humans for External Body															
EVs	Positions	Electric Field (V/m)			Magnetic Field (μT)			EVSEs	Positions	Electric Field (V/m)			Magnetic Field (μT)		
		Observed	Standards ICNIRP	IEEE C95.1	Observed	Standards ICNIRP	IEEE C95.1			Observed	Standard ICNIRP	IEEE C95.1	Observed	Standard ICNIRP	IEEE C95.1
EV1	Leg	137	5000	5000	1.92	200	75,800	EVSE1	Connector	321	5000	5000	445.1	200	904
	Torso	94	5000	5000	0.67	200	904		Battery	132	5000	5000	1.86	200	904
	Head	61	5000	5000	0.25	200	904								
	Dashboard	97	5000	5000	0.81	200	904								
	Rear Seat	84	5000	5000	1.1	200	904								
EV2	Chassis	124	5000	5000	1.0	200	904	EVSE2	Charger at 10 cm	845	5000	5000	155.2	200	904
	Leg	57	5000	5000	0.85	200	75,800		Charger at 60 cm	56	5000	5000	692.9	200	904
	Torso	64	5000	5000	1.56	200	904		Connector	197	5000	5000	62.04	200	904
	Head	36	5000	5000	0.8	200	904		Battery	100	5000	5000	20.44	200	904
	Dashboard	69	5000	5000	1.6	200	904								
EV3	Rear Seat	67	5000	5000	0.28	200	904		Charger at 10 cm	375	5000	5000	80.74	200	904
	Chassis	64	5000	5000	0.88	200	904		Charger at 60 cm	33	5000	5000	0.66	200	904
	Leg	97	5000	5000	1.75	200	75,800	EVSE3	Connector	294	5000	5000	73.43	200	904
	Torso	60	5000	5000	0.78	200	904		Battery	126	5000	5000	52.38	200	904
	Head	40	5000	5000	0.2	200	904								
EV4	Dashboard	76	5000	5000	0.7	200	904								
	Rear Seat	62	5000	5000	0.95	200	904		Charger at 10 cm	596	5000	5000	124.3	200	904
	Chassis	79	5000	5000	0.86	200	904	EVSE4	Charger at 60 cm	26	5000	5000	21.17	200	904
	Leg	49	5000	5000	0.98	200	75,800		Connector	22	5000	5000	54.26	200	904
	Torso	53	5000	5000	0.9	200	904		Battery	18	5000	5000	59.5	200	904
	Head	30	5000	5000	0.67	200	904								
	Dashboard	26	5000	5000	0.56	200	904								
	Rear Seat	19	5000	5000	0.4	200	904		Charger at 10 cm	24	5000	5000	88.3	200	904
	Chassis	33	5000	5000	0.89	200	904		Charger at 60 cm	16	5000	5000	0.17	200	904

Table 7
Comparison of Measurement and Computational Result of AC Charging Cable.

	Charger at 10 cm Distance					
	Electric Field Intensity (V/m)			Magnetic Flux Density (μ T)		
	Measurement	Computational	% Deviation	Measurement	Computational	% Deviation
EVSE1	845	832	1.5	155.2	132	14.9
EVSE3	596	690	15.77	124.3	123.7	0.48

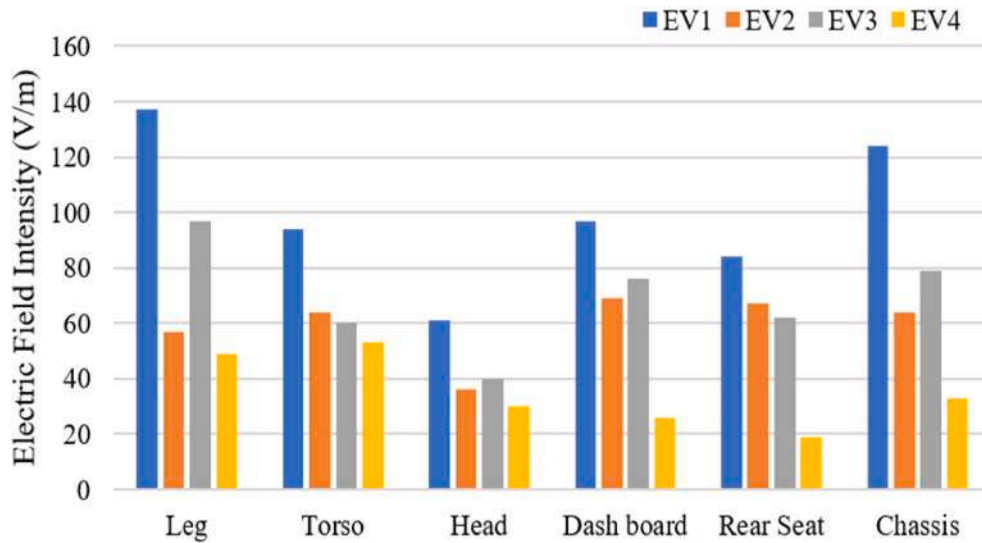


Fig. 4.1. Electric field comparison of different positions inside EVs.

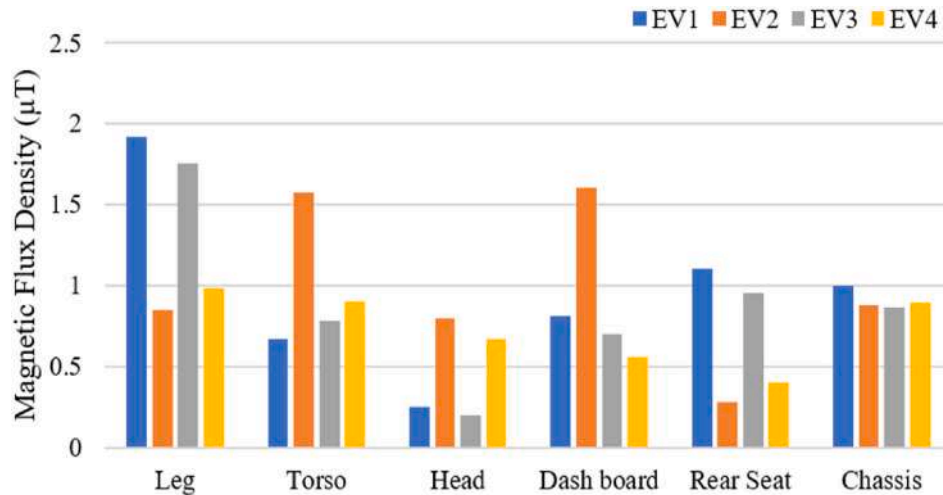


Fig. 4.2. Magnetic field comparison of different positions inside EVs.

the surrounding environment.

Mitigation techniques to minimize EMF emission includes industry and manufacturers bearing the responsibility of minimizing local peak EMF values and maintaining low average levels through intelligent vehicle design, particularly with respect to high-voltage components and power electronics. Optimized installation and routing of high-power cables within the limited space of a vehicle can play a crucial role in minimizing EMF emissions. Optimal Placement of EVSEs: As EMF intensity decreases rapidly with increasing distance, maintaining adequate separation from the source remains a fundamental and effective method of reducing exposure. Installing chargers with clearance from other electrical sources is necessary to avoid E and B fields and

their interferences. To avoid EMF radiation fields near charger and connector a proper shielding and grounding must be employed within power components and cables of EVSE. As a preliminary work, this paper addresses an important and underexplored issue in the context of electric vehicles and their supply equipment by measuring electromagnetic field exposure. Further in-depth analysis is required to confirm compliance with recommended exposure limits, prompting the standards for e-mobilities and long-term biological implications for humans.

6. Conclusions

The electromagnetic fields in the vicinity of EVs and EVSEs were

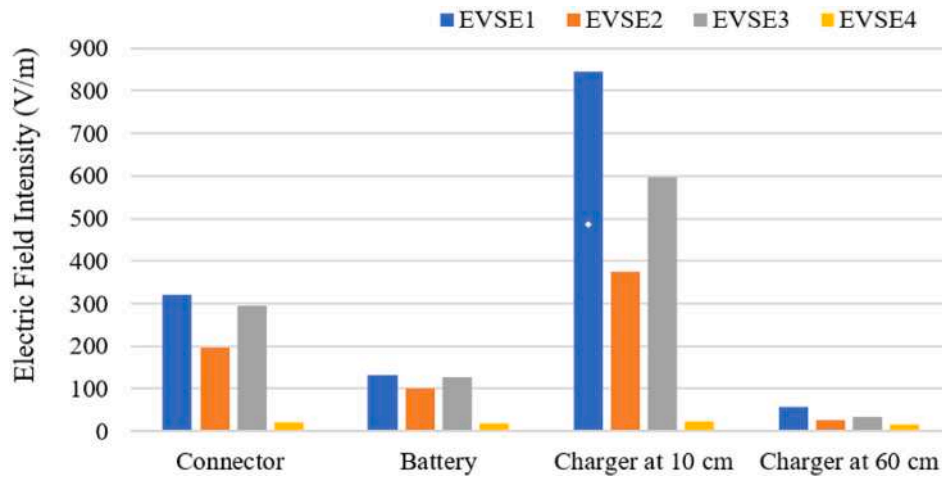


Fig. 4.3. Electric field comparison of different positions during charging in EVSEs.

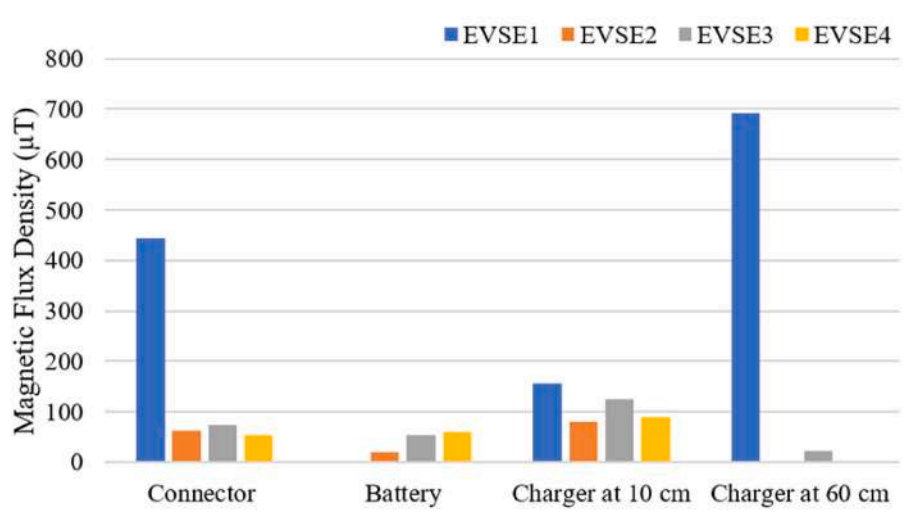


Fig. 4.4. Magnetic field comparison of different positions during charging in EVSEs.

measured and compared with standards in this present work. The electric and magnetic fields inside EVs whilst driving conditions fall under the standard limit of ICNIRP 2010 and IEEE Std C95.1. The electric field in the vicinity of all four EVSEs is also within the exposure limit. Conversely, magnetic flux density in the vicinity of connector and charger at 60 cm from EVSE1 exceeded the established standard threshold. This may be the proximity effect of EMI environments such as household water pumps and AC cables present in the apartment parking area.

As a part of preliminary work, simulation is performed to validate the measured results, with emphasis on the EVSEs' AC charging cable, which exhibits relatively high field strength. The analysis is performed using COMSOL Multiphysics®, a numerical software for EMF analysis, employing the FEM for modeling. The field distribution is investigated using the actual geometry of IEC Type 1 AC charging cable. At a distance of 10 cm from the EVSE charging cable, the simulated E and B exhibited close agreement with the measured values. The observed discrepancies may be attributed to the measuring instruments detecting electromagnetic emissions from other sources within the EVSE and EV systems. Regular monitoring of EMF emissions from a wide collection of EVs and EVSEs for different speeds and environmental conditions has to be done in future to overcome the limitations.

Policy recommendations to mitigate EMF exposure from EVs and EVSEs in the context of global electric vehicle Adoption

1. Adopt International Guidelines:

- National authorities should adopt and adapt international standard guidelines of ICNIRP as a basis for their own derived standards and regulations.
- Must adhere to IEC standards for designing and testing to achieve electromagnetic compatibility.

2. Vehicle and Charging Infrastructure Design:

- EV manufacturers and charging station developers must integrate EMC and EMF reduction strategies in their system design.
- This includes optimized cabling, shielding of high-voltage components, and intelligent placement of EVSE to minimize exposure.

3. Monitoring and Compliance:

- Routine EMF assessments should be mandated for both EVs and EVSEs in real-world operational conditions.
- Independent testing and certification bodies should verify compliance before market approval.

4. Public Safety and Awareness:

- Policies should mandate safe clearance around high-power charging stations, especially in sensitive environments such as schools and hospitals.
- Public awareness programs can help educate EV users about safe charging practices and the importance of compliance with EMF guidelines.

5. Encourage Research and Standard Updates:

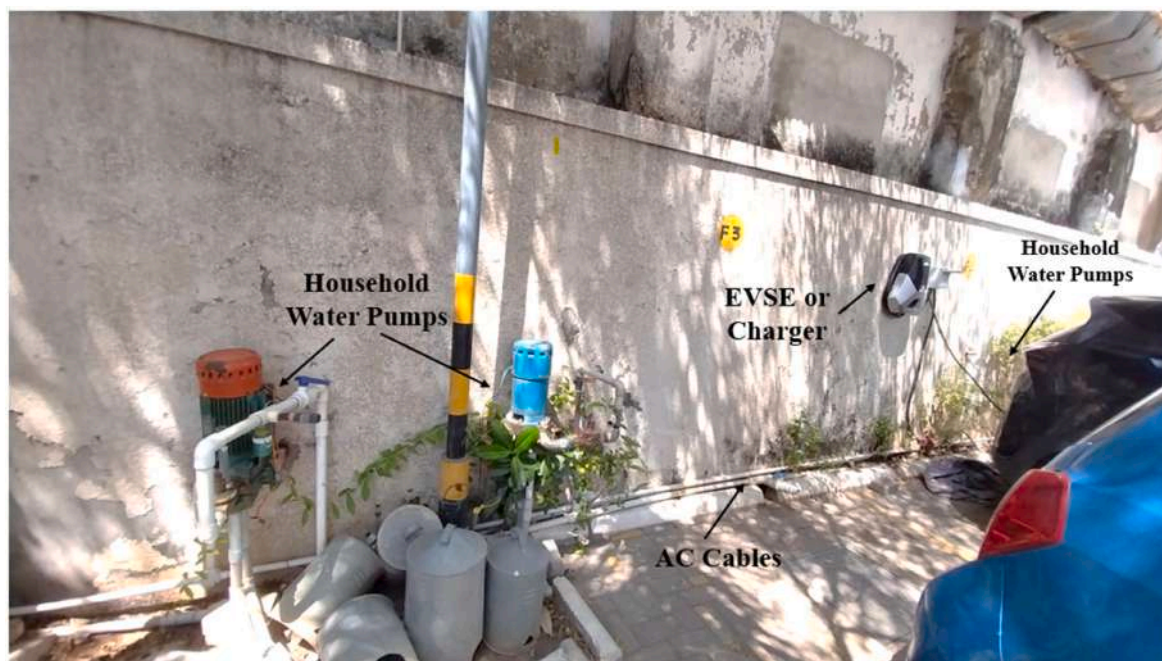


Fig. 4.5. Household Water Pumps and AC Cables in the EVSE Vicinity.

- Given the rapid advancements in high-power fast charging and wireless charging equipment, regulators should support ongoing research on EMF and EMI impacts.
- Exposure standards should be periodically updated to reflect the latest scientific evidence and technological developments.

Scope of future work

- Long-term monitoring/measurement of EMF exposure for a wide group of EVs and EVSEs has to be done due to worldwide adoption of electric vehicles.
- Developing mitigation techniques for high EMF levels and prompting the development of EMF measurement standards for EV and EVSE.
- A detailed computational analysis of electromagnetic field distribution pattern on external human body during vehicle charging and while seated inside the electric vehicle has to be done for human safety. Additionally, research has to be carried out on the impact of EVs and EVSEs on the active implanted medical devices inside the human body.
- The EMF exposure studies have to be performed in different atmospheric conditions, such as humidity, temperature, and pressure, while driving and charging an EV, including leakage currents during rain.
- Due to the advancements of DC fast chargers, the effects of electrostatic and magnetostatic fields need to be investigated.
- An experimental in-depth animal study for internal body field exposure levels for different organs and its effect has to be analyzed.

CRediT authorship contribution statement

Gowthama Priya Punniya Murthy: Writing – review & editing, Writing – original draft, Software, Methodology, Formal analysis, Data curation. **Gowri Sree Varadarajan:** Conceptualization, Visualization, Validation, Supervision, Resources, Project administration, Investigation.

Declaration of competing interest

The authors declare that they have no known competing financial

interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgement

I would like to thank the All India Council for Technical Education for awarding the AICTE Doctoral Fellowship to do my research work.

I would like to thank DST-FIST for funding the purchase of Field Meters.

I would like to thank Government of India, MHRD-SPD-RUSA, Tamil Nadu for RUSA 2.0 (Rashtriya Uchchatar Shiksha Abhiyan) scheme for funding the purchase of COMSOL Multiphysics® software.

Data Availability

Data will be made available on request.

References

- [1] A.F. Pennington, C.R. Cornwell, et al., Electric vehicles and health: a scoping review, *Environ. Res.* 251 (Part 2) (2024) 118697.
- [2] M.A.I. Malik, M.A. Kalam, et al., Energy transition towards electric vehicle technology: recent advancements, *Energy Rep.* 13 (2025) 2958–2996.
- [3] IEA, 2025. International Energy Agency. Trends in electric car markets. <https://www.iea.org/reports/global-ev-outlook-2025/trends-in-electric-car-markets-2>.
- [4] I. Aretxabaleta, et al., High-voltage stations for electric vehicle fast-charging: trends, standards, charging modes and comparison of unity power-factor rectifiers, *IEEE Access* 10 (2021) 1109.
- [5] P.R. Satpathy, et al., Technological innovations and sustainable strategies for advancing electric vehicle performance and market integration, *Energ. Strat. Rev.* 60 (2025) 101790.
- [6] J. Moon, H. Anwar, et al., Electrified fleet and infrastructure aware energy efficient routing, *eTransportation* 22 (2024) 100351.
- [7] T. Unterluggauer, et al., Electric vehicle charging infrastructure planning for integrated transportation and power distribution networks. A review, *Etransportation*. 12 (2024) 100163.
- [8] IEA, 2024. International Energy Agency. Outlook for electric vehicle charging infrastructure. <https://www.iea.org/reports/global-ev-outlook-2024/outlook-for-electric-vehicle-charging-infrastructure>.
- [9] Hendri Maja Saputra et al., Characterization of plugging and unplugging process for electric vehicle charging connectors based on Force/Torque measurements, *Measurement*, 242 (2025) Part B, 115876. <https://doi.org/10.1016/j.measurement.2024.115876>.
- [10] S.S.G. Acharige, et al., Review of electric vehicle charging technologies, standards, architectures, and converter configurations, *IEEE Access* 11 (2023) 41218–41255.

- [11] SAE, 2017. SAE Electric Vehicle and Plug in Hybrid Electric Vehicle Conductive Charge Coupler, Standard J1772_201710.
- [12] SAE, 2024. SAE Electric Vehicle and Plug in Hybrid Electric Vehicle Conductive Charge Coupler, Standard J1772_202401.
- [13] IEC 61851-1, International Electrotechnical Commission, Electric Vehicle Conductive Charging System - Part 1, General Requirements, Geneva, Switzerland, 2017.
- [14] IEC 62196-1, 2022. Plugs, socket-outlets, vehicle connectors and vehicle inlets - Conductive charging of electric vehicles - Part 1: General requirements.
- [15] IEC 62196-2, 2022. Plugs, socket-outlets, vehicle connectors and vehicle inlets - Conductive charging of electric vehicles - Part 2: Dimensional compatibility and interchangeability requirements for A.C. pin and contact-tube accessories.
- [16] IEC 62196-3, 2022. Plugs, socket-outlets, vehicle connectors and vehicle inlets - Conductive charging of electric vehicles - Part 3: Dimensional compatibility and interchangeability requirements for D.C. and A.C./D.C. pin and contact-tube vehicle couplers.
- [17] IEC 61851-23, 2023. DC electric vehicle supply equipment. Electric vehicle conductive charging system - Part 23.
- [18] IS17017, 2018. Electric Vehicle Conductive Charging System Standards. Bureau of Indian Standards.
- [19] BIS, 2018. Bureau of Indian Standards. Standards for electric vehicle Charging. <https://e-amrit.niti.gov.in/bis-standard>.
- [20] IEC 61851-21-1, 2017. Electric vehicle on-board charger EMC requirements for conductive connection to AC/DC supply. Electric vehicle conductive charging system - Part 21-1.
- [21] IEC 61851-21-2, 2018. EMC requirements for off board electric vehicle charging systems. Electric vehicle conductive charging system - Part 21-2.
- [22] CEA, Central Electricity Authority. Automotive Industry Standard AIS 138 part1&2, India.
- [23] ISO 43.120, 2001. International Organization for Standardization. Electric Road Vehicles Including their Components and Systems.
- [24] Konstantinos Pliakostathis, Research on EMI from Modern Electric Vehicles and their Recharging Systems. IEEE Xplore. International Symposium on Electromagnetic Compatibility - EMC EUROPE, 2020.
- [25] C.A. Marshman, et al., Electromagnetic Compatibility and Electromagnetic Field issues for FEVs. IEEE Xplore. 5th IET Hybrid and Electric Vehicles Conference, 2015.
- [26] Seongho Woo et al., Design of resonant circuit components to suppress both EMF and EMI in wireless power transfer systems for electric vehicles, IEEE J. Emerg. Select. Top. Power Electron., Volume: 13 (2025) Issue: 4.
- [27] Mahmoud M. Elymany et al., Safety assessment of electromagnetic fields of different transmitters and receivers for EVs static charging. Scient. Rep. volume 15 (2025) Article number: 15193.
- [28] V. Prasad Kodali, Engineering Electromagnetic Compatibility, Principles, IEEE Electromagnetic Compatibility Society, Sponsor, Measurements and Technologies. Dept. of Electronics Govt. of India, 1996.
- [29] A.R. Ruddle et al., Investigation of human exposure to magnetic fields from electrical powertrains: measured exposure levels and simulated impact on human body, in: 5th Hybrid and Electric Vehicles Conference. London, UK, 2014. DOI: 10.1049/cp.2014.0956.
- [30] M.E. Maffei, Magnetic fields and cancer: epidemiology, cellular biology, and theranostics, Int. J. Mol. Sci. 23 (3) (2022) 1339, <https://doi.org/10.3390/ijms23031339>.
- [31] National Cancer Institute, USA.gov. Electromagnetic Fields and Cancer. <https://www.cancer.gov/about-cancer/causes-prevention/risk/radiation/electromagnetic-fields-fact-sheet>.
- [32] WHO, Framework for developing health-based EMF standards, World Health Org. Geneva, Switzerland, 2006.
- [33] WHO, 2007. Electromagnetic Fields and Public Health: Extremely low frequency fields. Environmental Health Criteria Monograph No. 238. Geneva, Switzerland.
- [34] G. Betta, et al., Experimental investigation on workers' exposure to electromagnetic fields in proximity of magnetic resonance imaging systems, Measurement 45 (2) (2012) 199–206, <https://doi.org/10.1016/j.measurement.2011.03.001>.
- [35] ICNIRP, Guidelines for limiting exposure to time-varying electric and magnetic fields (1 Hz–100 kHz), Health Phys. 99 (6) (2010) 818–836.
- [36] IARC Monographs on the Evaluation of Carcinogenic Risks to Humans. Vol. 80. Non-ionizing radiation, Part 1: Static and extremely low-frequency (ELF) electric and magnetic fields. IARC Working Group. Lyon, 2002.
- [37] IEEE C95.1-2019. Standard for Safety Levels with Respect to Human Exposure to Electric, Magnetic, and Electromagnetic Fields, 0 Hz to 300 GHz. DOI: 10.1109.
- [38] N. Damijan, et al., Electric properties of tissues, Wiley Encyclopaedia of Biomedical Engineering (2006), <https://doi.org/10.1002/9780471740360.ebs0403>.
- [39] M. Otto, K.E. von Muhlendahl, Electromagnetic fields (EMF): do they play a role in children's environmental health (CEH)? Int. J. Hyg. Environ. Health 210 (2007) 635–644, <https://doi.org/10.1016/j.ijheh.2007.07.007>.
- [40] J.G. Gurney, E. van Wijngaarden, Extremely low frequency electromagnetic fields (EMF) and brain cancer in adults and children: review and comment, Neuro Oncology. 1 (3) (1999) 212–220, <https://doi.org/10.1093/neuonc/1.3.212>.
- [41] Hydro-Quebec, 2011. The Power System and Health: Electric and Magnetic Fields.
- [42] S. Abtin, et al., A review on the consequences of molecular and genomic alterations following exposure to electromagnetic fields: Remodeling of neuronal network and cognitive changes, Brain Res. Bull. 217 (2024) 111090.
- [43] IEEE Std 1140 – 1994. IEEE Standard Procedures for the Measurement of Electric and Magnetic Fields from Video Display Terminals (VDTs) from 5 Hz to 400 kHz.
- [44] IEEE Std 644 - 2019. IEEE Standard Procedures for Measurement of Power Frequency Electric and Magnetic Fields from AC Power Lines.
- [45] <https://www.volex.com/products-and-services/electric-vehicle-charging-solutions/ev-ac-charging-cables/type-1-iec-tethered-ev-ac-charging-cables/>.
- [46] K. Gryz, J. Karpowicz, et al., Complex electromagnetic issues associated with the use of electric vehicles in urban transportation, Sensors 22 (2022) 1719.
- [47] N. G. Ptitsyna, A. Ponzetto, et al., Electric vehicle magnetic fields and their biological relevance, J. Scient. Res. Rep. 3(13) (2014) 1753-1770, Article no. JSRR.2014.13.004.
- [48] L. Yang, Lu. Meng, J. Lin, et al., Long-term monitoring of extremely low frequency magnetic fields in electric vehicles, Int. J. Environ. Res. Public Health 16 (2019) 3765.
- [49] H. Fukui, et al., Magnetic field measurement of various types of vehicles, including electric vehicles, Electronics 14(15), 2936 (2025) 10.3390/electronics14152936.
- [50] R.-P. Fotesco, et al., Electromagnetic and Electric Field Radiation inside Electric Vehicles and Classic Vehicles, in: IEEE 28th International Symposium for Design and Technology in Electronic Packaging (SIITME), 2022, <https://doi.org/10.1109/SIITME56728.2022.9988730>.
- [51] Hongguk Bae, Sangwook Park, Assessment of the electromagnetic radiation exposure at ev charging facilities. Sensors 2023, 23(1), 162; <https://doi.org/10.3390/s23010162>.
- [52] R. Armstrong, et al., The effect of fully electric vehicles on the low frequency electromagnetic environment, IEEE International Symposium on Electromagnetic Compatibility (EMC) (2015), <https://doi.org/10.1109/ISEMC.2015.7256242>.
- [53] M. Maslanyj, T. Lightfoot, J. Schüz, Z. Sienkiewicz, A. McKinlay, A precautionary public health protection strategy for the possible risk of childhood leukaemia from exposure to power frequency magnetic fields, BMC Public Health 10 (2010) 673.
- [54] J. Schuz, Exposure to extremely low-frequency magnetic fields and the risk of childhood cancer: update of the epidemiological evidence, Prog. Biophys. Mol. Biol. 107 (2011) 339–342.
- [55] Murat Terzi, Berra Ozberk, et al., The role of electromagnetic fields in neurological disorders, J. Chem. Neuroanatomy Volume 75 (2016) Part B, Pages 77–84.
- [56] M. Carlberg, et al., Case-control study on occupational exposure to extremely low-frequency electromagnetic fields and the association with acoustic neuroma, Environ. Res. 187 (2020) 109621.
- [57] N. Augera, et al., Residential exposure to electromagnetic fields during pregnancy and risk of child cancer: a longitudinal cohort study, Environ. Res. 176 (2019) 108524.
- [58] N. Pasquino, Measurement and analysis of human exposure to electromagnetic fields in the GSM band, Measurement 109 (2017) 373–383, <https://doi.org/10.1016/j.measurement.2017.06.003>.