



Review

From Measurement to Health: A Synthesis of EMF Exposure, Biological Evidence, and Safety Guidelines in Electric Vehicles

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Highlights

Public health relevance—How does this work relate to a public health issue?

- Electric vehicles (EVs) are replacing conventional cars worldwide, exposing a growing number of occupants daily to complex electromagnetic fields generated by high-voltage batteries, cables, and motors.
- Some magnetic field levels measured inside EVs, particularly near the floor, footwell, and rear seats, overlap with exposure levels associated with adverse health outcomes in residential, occupational, and laboratory studies.

Public health significance—Why is this work of significance to public health?

- This study helps connect real-world EV cabin magnetic field measurements with recent evidence on the biological and health effects of comparable low-frequency exposure, addressing an area that remains underexplored in both the literature and regulatory frameworks.
- Future health protection efforts may need to focus on certain groups, including children, who often sit in the rear seats where field levels can be highest, and professional drivers and regular commuters, who are exposed repeatedly over time.

Public health implications—What are the key implications or messages for practitioners, policy makers and/or researchers in public health?

- Existing exposure guidelines (ICNIRP, IEEE) primarily address established short-term effects (e.g., nerve stimulation) and offer limited guidance for interpreting the complex, variable exposure conditions unique to EVs or their potential long-term impacts, highlighting the need for refinement as EV-specific research accumulates.
- Future research would benefit from adopting standardized, occupant-specific exposure assessments (e.g., following IEC 62764-1), studying frequent EV occupants, and giving closer attention to vulnerable groups such as children to support ongoing evaluations of safety standards.



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Abstract

The expanding global adoption of electric vehicles (EVs) has raised an understudied public health concern regarding extended occupant exposure to complex electromagnetic fields (EMFs) from high-voltage components such as battery packs, electric motors, and power electronics within the enclosed vehicle cabin. This study provides a risk assessment by integrating a review of international safety guidelines, recent in-cabin EMF measurements from battery electric vehicles, and current evidence on the biological and health effects of comparable EMF exposure. The synthesized data reveal that while EV magnetic fields

remain well below the established safety limits, certain biological and adverse health outcomes may occur at levels measured in EV cabins. Notably, rear seat exposures frequently exceed the 0.4 μ T level associated with an increased risk of childhood central nervous system tumors, while similarly weak magnetic fields can displace magnetic particles in human brain tissue, which may in turn contribute to cellular damage. Additionally, field levels near the EV footwell approach intensities reported to induce pro-inflammatory immune responses in human cells, and comparable occupational exposures are linked to higher blood pressure and poorer sleep quality. In addition, field levels tend to peak during acceleration and at higher speeds, creating conditions where maximum field exposure and driving-related stress may occur simultaneously. This dynamic closely parallels recent occupational findings showing that higher magnetic field exposure combined with mental stress significantly increases cardiovascular risks. This compounding effect represents an unexamined vulnerability for drivers that current safety frameworks do not address. Overall, the evidence suggests that magnetic field exposure during routine EV use should not be presumed harmless and highlights the need for targeted research priorities, including health tracking of frequent users, dedicated analysis of children as a vulnerable subgroup, and laboratory investigations using exposure patterns representative of real EV environments. Adopting standardized measurement protocols (e.g., IEC 62764-1:2022) and integrating new findings into future safety guidelines would further strengthen research comparability and regulatory adequacy, ultimately benefiting human health.

Keywords: electric vehicles (EVs); electromagnetic fields (EMFs); EMF measurement; health effects; safety guidelines; public health

1. Introduction

Electric vehicles (EVs) have emerged as a promising alternative to conventional internal combustion engine (ICE) vehicles. The primary reason behind this emergence is the environment. Unlike ICE vehicles, EVs do not produce exhaust fumes, which helps reduce air pollution and cut carbon emissions from transportation. Beyond their ecological benefits, EVs also bring practical benefits for drivers. They cost less to run, need less maintenance, and offer smooth and quiet acceleration. These benefits have fueled rapid growth in their popularity. According to the International Energy Agency (IEA), global EV sales grew by 20% in 2025, exceeding 20 million vehicles and accounting for one-quarter of all new cars sold [1]. Europe saw the biggest rise, with EV sales growing by over 30% and reaching 28% of all cars sold. China continued to dominate, with EVs representing nearly 55% of sales. In the United States, sales remained stable at nearly 10% of all cars sold. While the near-term outlook is uncertain, the IEA projects that under current policy settings, the EV share of global sales will reach around 50% by 2035.

This shift towards EVs, however, also raises a less discussed public health concern. EVs create electromagnetic fields (EMFs) while operating, and people inside the car are exposed to them for long periods in a small, enclosed space. Unlike gasoline cars, EVs use many high-voltage parts such as large battery packs, thick power cables, and inverters. These components generate EMFs of varying strength when the car is running. Because passengers sit close to these sources inside the cabin, there may be health risks from long-term, low-level exposure [2,3].

The EMFs inside EVs are complex and constantly changing. They are a mixture of static and time-varying fields across a broad spectrum of frequencies, making them very different from the steady fields from a power line. This happens because the fields originate

from many different sources at the same time, and their intensity changes constantly with the car's movements, such as accelerating, braking, or turning. This environment becomes even more crowded as manufacturers add advanced features such as driver-assistance systems and self-driving capabilities.

The complex electromagnetic nature of EVs has raised increasing public concern about potential health effects from EMF exposure. For decades, researchers have studied how EMF might influence the human body. For example, studies have looked at possible links to cancer [4,5], changes in brain activity [6,7], and impacts on reproduction [8,9]. Despite extensive research, scientists have not reached definitive conclusions about the health risks of EMF exposure, particularly regarding long-term effects. Established short-term effects vary with frequency. At radiofrequencies, high enough exposures can cause heating effects in body tissues. At low frequencies, high enough exposures can create electric fields and currents inside the body, which may stimulate nerves and muscles. The potential health effects of long-term exposure to weaker low-frequency EMFs, such as those present in EVs, remain less clear.

A growing number of studies have investigated EMF exposure in different EV models, analyzing how field strength changes during acceleration, cruising, deceleration, and other common driving conditions [10–15]. Some of these studies revealed that magnetic fields inside the cabin can be higher than 0.4 microteslas (μT), which is alarming because past epidemiological studies have linked residential exposures above this level to increased incidence of childhood leukemia [16,17], although the overall evidence remains limited. However, these measured levels in EVs remain well below the safety limits established by international health organizations such as the International Commission on Non-Ionizing Radiation Protection (ICNIRP), which set these limits to prevent short-term, well-established biological effects such as tissue heating and nerve stimulation. While there are no immediate dangers, people who regularly travel in EVs may face cumulative exposure over a long period of time, raising concerns similar to those associated with chronic low-frequency EMF exposure in residential and occupational settings. This underscores a critical need for targeted research on EVs to determine whether their unique electromagnetic exposure patterns are linked to any harmful health effects.

Conducting such research demands standardized measurement methodologies to ensure that results can be reliably compared across different studies and vehicle models. There is currently no single international document that every regulatory body has officially adopted as the universal human exposure measurement procedure for vehicles. The most direct and specific international standard available for assessing human exposure to EMFs generated by road vehicles is IEC 62764-1:2022, published by the International Electrotechnical Commission (IEC). It was created to establish a unified framework for measuring the exposure to multiple magnetic field sources in automotive settings and applies broadly to passenger cars and light commercial vehicles, including EVs [18]. It specifies distinct measurement methods for magnetic fields under different conditions, including when the vehicle is stationary, when it is moving, and when it is charging. Despite the availability of the IEC methodology, studies of magnetic field measurement using this standard remain scarce, indicating the need for wider recognition and use in future research efforts [19].

This lack of widespread implementation of standardized measurement protocols reflects a broader challenge in EMF regulation. Because scientists still do not fully understand the possible health risks of long-term exposure to low-level EMFs, countries have taken very different approaches to setting safety limits [20]. Most governments rely on guidance from two main organizations. The first is the ICNIRP, an independent scientific body that issues safety recommendations adopted by many countries [17,21–23]. The second is the

Institute of Electrical and Electronics Engineers (IEEE), which issues detailed standards in the C95 series [24,25]. As a result, regulations around the world vary widely. Many countries directly adopt ICNIRP's guidelines, while others set their own limits that closely follow either the ICNIRP or the IEEE recommendations [26,27]. Some regions and countries restrict their exposure limits to specific power infrastructure, such as the boundaries of transmission line rights-of-way, rather than adopting whole exposure guidelines for all sources [28]. Further details on differences in adoption and implementation across countries can be found in the Appendix A.

The convergence of rapidly growing EV adoption, the complex electromagnetic environments these vehicles generate, emerging evidence of biological effects from specific field configurations, and the lack of unified international measurement standards and regulatory frameworks highlight the need for a review of current knowledge in this field. This study aims to address that need through three main objectives. First, we summarize the major regulations and guidelines that define recommended exposure limits for EMF, focusing on the standards developed by the ICNIRP and the IEEE and examining how these international guidelines have been adopted globally. Building on this regulatory foundation, we then conduct a two-part review of the related literature. We examine the most recent studies measuring EMFs inside EVs and survey the existing evidence on the biological and health effects of low-frequency EMF exposure. Finally, we integrate these areas to assess whether the low-frequency EMFs in EVs might affect occupant health, considering both the measured field levels and the established exposure limits. Our study focuses specifically on fully electric vehicles, also known as battery EVs or pure EVs, rather than hybrid or plug-in hybrid models. By integrating evidence and analysis across these three domains, this work offers an assessment of current knowledge on human exposure to EMFs in EVs and outlines directions for long-term studies on health outcomes among EV users, with the goal of refining future safety guidelines.

2. Regulatory Framework

2.1. ICNIRP Guidelines

The evolution of the ICNIRP standards shows how the organization has steadily adapted to both scientific progress and technological change. In the 1990s, ICNIRP published two major guidelines. One addressed static magnetic fields (SMFs) [29], and the other covered time-varying EMFs up to 300 gigahertz (GHz) [30]. Although separating static fields, such as those produced by magnets or direct current (DC), from time-varying fields, such as those from alternating power lines or radio waves, offers simplicity, this approach does not adequately reflect the reality that different frequency ranges affect the human body in varying ways [31,32]. From 2009 to 2020, ICNIRP gradually replaced the earlier two guidelines with four specialized ones [17,21–23]. These updates were necessary to address new exposure patterns from emerging technologies. During this time, EVs and advanced wireless technology became popular. They created new patterns of electromagnetic exposure that the previous guidelines did not adequately address [33–35].

Each of the current guidelines targets a specific range of frequencies and exposure situations. The 2009 version, updating the 1994 guidelines, focuses on SMF at 0 hertz (Hz) and is essential for assessing exposure near high-current DC components such as battery packs and fast-charging systems [21]. The 2010 guidelines replaced the low-frequency portion of the 1998 guidelines and cover time-varying fields from 1 Hz to 100 kHz, including the frequencies most relevant to EV powertrains, such as motors, power electronics, and wireless charging systems [17]. Then, the 2014 guidelines address the short-term physiological effects that can occur when people move within static or very low frequency (<1 Hz) fields, such as when a driver or passenger shifts position near the vehicle's battery. Unlike

the 2009 document, which sets limits on the strength of the external SMF, this 2014 version focuses on the internal electric fields induced by body movement within a static field or by exposure to slowly changing fields. It complements the 2009 guidelines by addressing these motion-related effects, and together the two guidelines provide a complete framework for assessing exposure to SMF. The most recent guidelines, published in 2020, replaced the high-frequency portion of the 1998 standard. They apply to radiofrequency fields from 100 kHz to 300 GHz and address high-frequency wireless communications in vehicles, such as Wi-Fi, Bluetooth, and V2X technologies [23]. Despite the 1998 document being superseded, some countries still use it for EMF assessment, because their local standards have not yet been updated. The combined scope of these four guidelines is now more comprehensive than it was in the 1990s. Evaluating EMF exposures in the EV environment therefore involves considering multiple current ICNIRP standards. An overview of the current ICNIRP guidelines is presented in Table 1.

Table 1. Overview of ICNIRP Exposure Guidelines.

Year	Document Title	Frequency Range
2009	Guidelines on Limits of Exposure to Static Magnetic Fields	0 Hz (Static/DC)
2010	Guidelines for Limiting Exposure to Time-Varying Electric and Magnetic Fields (1 Hz–100 kHz)	1 Hz–100 kHz
2014	Guidelines for Limiting Exposure to Electric Fields Induced by Movement of the Human Body in a Static Magnetic Field and by Time-Varying Magnetic Fields Below 1 Hz	<1 Hz & Motion in a static (0 Hz) field
2020	Guidelines for Limiting Exposure to Electromagnetic Fields (100 kHz to 300 GHz)	100 kHz–300 GHz

Among the applicable EMF standards for EVs, the ICNIRP 2010 guidelines for time-varying fields (1 Hz–100 kHz) is the most relevant for evaluating passenger and public exposure to EMF, since it covers the main operational frequencies of an EV's biggest sources of EMF [34]. For example, it includes the frequencies produced by the vehicle's power electronics, such as the inverter that powers the motor [36]. These components, along with the motor's operating frequency and the high-current cables, create a complex magnetic field environment that largely falls under the 2010 guidelines.

In contrast, both static fields and radiofrequency (RF) emissions contribute relatively little to overall electromagnetic exposure in EVs. While battery packs do generate static fields proportional to the DC flow, these fields weaken rapidly with distance and are substantially attenuated by a vehicle's metal enclosure and floorboard. Tests show these fields inside EVs are only slightly stronger than Earth's natural magnetic field [33]. RF emissions from a vehicle's communication and entertainment systems are engineered to comply with human exposure limits. Published measurements show that RF field strengths inside EVs are typically similar to those commonly measured in homes and offices [33,37,38].

Field measurements during driving consistently show that electromagnetic exposure inside EVs is dominated by low (<2 kHz) and intermediate-frequency (2–100 kHz) sources from electric motors and power electronics, rather than static fields or RF emissions [33,34,39]. Therefore, while a complete risk assessment must consider all relevant frequency ranges, research on EMF exposure in EVs has focused on measuring low-

and intermediate-frequency fields and assessing their compliance with the 2010 ICNIRP guidelines [15,40].

The ICNIRP 2010 guidelines for exposure to time-varying electric and magnetic fields (1 Hz–100 kHz) provide the primary reference framework for assessing EMF exposure in EVs. This frequency range is especially relevant for EVs because their powertrains, batteries, and wireless charging systems typically operate from DC (0 Hz) up into the kilohertz range [33,34,41,42].

The guidelines establish two types of exposure limits that together provide protection: basic restrictions and reference levels. Basic restrictions define how much electric field can be induced within the body's tissues by external magnetic fields, since strong internal electric fields can affect nerves and muscles. However, they cannot be measured directly and require computational modeling to evaluate. To make compliance assessment easier, ICNIRP also defines reference levels as limits for external EMF strengths that can be measured using standard equipment such as field meters. These limits are derived from basic restrictions using conservative exposure modeling. Meeting the more easily measured reference levels ensures compliance with the underlying basic restrictions and typically results in much lower exposure as the reference levels are based on conservative safety assumptions [17]. Even when external fields reach the reference levels, the actual induced internal fields are typically much lower than the basic restrictions, providing extra protection against established health effects.

The reference levels vary with frequency. This is because different frequencies penetrate the body differently and nerves respond differently to various frequencies. These limits are expressed in terms of electric field strength, magnetic field strength, and magnetic flux density. Electric field strength (E) is measured in volts per meter (V/m). It tells us how strongly an electric field can create currents or voltages inside the body. Magnetic field strength (H) is measured in amperes per meter (A/m). It represents how intense a magnetic field is when created by electric currents or magnetic materials. Magnetic flux density (B) is measured in tesla (T) or μT . It measures the total magnetic effect in a given area. In non-magnetic materials such as air and biological tissues, magnetic flux density (B) and magnetic field strength (H) are directly proportional to each other. This means when one increases, the other increases by the same proportion. Therefore, for safety assessments, describing the magnetic field using either B or H alone is sufficient [17].

The guidelines define separate limits for occupational and general public exposure with lower allowable levels applied to the latter. Occupational limits apply to workers who are trained adults and are aware of exposure conditions. General public limits cover people of all ages and health conditions, including sensitive groups such as children, pregnant women, and the elderly, and are therefore the appropriate reference standard for EV exposure assessments. These stricter limits ensure safety for all passengers. For a comprehensive summary of these thresholds across the 1 Hz to 10 MHz frequency spectrum, readers are referred to Table 3 for occupational exposure and Table 4 for general public exposure in the ICNIRP 2010 guidelines [17].

As illustrative examples from those tables, within the very low frequency range of 1–8 Hz, the magnetic flux density (B) reference level for the general public is $0.04/f^2$ T, corresponding to 40 milliteslas (mT) at 1 Hz and decreasing to approximately 0.625 mT at 8 Hz. The associated magnetic field strength (H) in this range is $3.2 \times 10^4/f^2$ A/m, which equals 32,000 A/m at 1 Hz and 500 A/m at 8 Hz. The electric field strength (E) limit is 5 kV/m. For occupational exposure, the corresponding limits are higher, the magnetic flux density is $0.2/f^2$ T, corresponding to 200 mT at 1 Hz and 3.125 mT at 8 Hz, with the equivalent magnetic field strength of $1.63 \times 10^5/f^2$ A/m (i.e., 163,000 A/m at 1 Hz). The electric field limit remains constant at 20 kV/m in this frequency band. At power line

frequencies of 50 Hz (used in most of the world) and 60 Hz (used in North America), the reference magnetic flux density for the general public is 200 μT (2×10^{-4} T), corresponding to a magnetic field strength of approximately 160 A/m. The corresponding electric field strength limit is 5 kV/m at 50 Hz and approximately 4.17 kV/m at 60 Hz. Occupational exposure permits higher limits, including a magnetic flux density of 1 mT (1×10^{-3} T), a magnetic field strength of approximately 800 A/m, and an electric field strength of 10 kV/m at 50 Hz, decreasing to about 8.3 kV/m at 60 Hz.

Overall, these frequency-dependent reference levels establish practical, measurable limits for external electric and magnetic fields. By keeping induced internal electric fields below harmful thresholds, they prevent nerve and muscle stimulation at low frequencies and excessive tissue heating at higher frequencies.

2.2. IEEE Standards

The IEEE has played a leading role in setting safety standards for human exposure to EMF since the early 1980s [25,43]. The first official standard, issued in 1982 and covering frequencies from 300 kHz to 100 GHz, introduced frequency-dependent limits and was the earliest to differentiate workers and the public by setting tougher safety limits for the public [44].

Throughout the 1990s and 2000s, the IEEE standards evolved to incorporate better scientific understanding. The 1991 update expanded the frequency range to span from 3 kHz to 300 GHz and refined how energy absorption in body tissue is measured and limited [45]. In 2002, a companion standard called IEEE C95.6-2002 was created specifically to cover the frequency range from 0 Hz up to 3 kHz, covering exposures from sources such as power lines, household appliances, and medical imaging systems [24]. Building on these foundations, the 2005 edition (IEEE C95.1-2005), covering 3 kHz to 300 GHz, incorporated new research from the cell phone boom of the 1990s to update exposure limits for modern wireless technologies [46–48]. This revision also aligned the standard more closely with international guidelines, especially ICNIRP's, making it easier for global companies to meet both U.S. and international requirements [49].

The most recent and comprehensive revision was released in 2019 as IEEE C95.1-2019 [25]. This standard covered the complete electromagnetic spectrum from 0 Hz to 300 GHz, replacing earlier segmented standards. It specifies internal dosimetric reference limits (DRLs), similar to ICNIRP's basic restrictions, for induced electric fields inside the exposed body and uses exposure reference levels (ERLs), similar to ICNIRP's reference levels, to ensure these internal limits are met. Both DRLs and ERLs aim to prevent painful electrostimulation in the 0 Hz–5 MHz range and excessive heating in the 100 kHz–300 GHz range [43]. For EVs, the low-frequency portion of the standard is particularly relevant for evaluating magnetic fields generated by high-power equipment such as inverters, including those caused by movement [50–52]. Although some regulators still use older versions, the 2019 revision makes it easier to evaluate complex electromagnetic exposures in today's vehicles and other environments [53].

As noted, the IEEE C95.1-2019 standard uses distinct sets of exposure limits for two environments. The first set applies to restricted environments where people who are exposed know about the potential exposure. This typically applies to workplaces where workers are trained and informed about EMF exposure. The second set applies to unrestricted environments where the general public may be exposed, including the passenger spaces within all vehicles. Unrestricted environment limits are set much lower than those for restricted environments to protect the diverse general public of all ages and all health conditions [25]. Similar to ICNIRP's reference levels, the exposure limits (ERLs) in the IEEE C95.1-2019 standard vary with frequency and provide thresholds for external fields

expressed in terms of electric field strength (E, V/m), magnetic field strength (H, A/m), and magnetic flux density (B, mT or T). However, while the ICNIRP applies uniform limits across the body, the IEEE differentiates magnetic field limits by body part, with stricter protections for the head and torso and more relaxed limits for limbs. For the complete ERLs for EV-relevant low frequencies (0 Hz–100 kHz), readers are referred to Table 2 for the head and torso and Table 3 for the limbs in IEEE C95.1-2019 [25].

As illustrative examples from those tables, for head and torso exposures, the allowable magnetic flux density (B-field) in unrestricted public environments between 0.153 Hz and 20 Hz is defined by $18.1/f$ mT, yielding 18.1 mT at 1 Hz and decreasing to 2.26 mT at 8 Hz. The corresponding magnetic field strength (H) over this interval is $14,400/f$ A/m, giving 14,400 A/m at 1 Hz and 1800 A/m at 8 Hz. In restricted environments, the limits are higher, $54.3/f$ mT and $43,200/f$ A/m, respectively. Conversely, the limits for limb exposures are much less strict. For example, at frequencies below 10.7 Hz, the allowable B-field for limbs is 353 mT in both unrestricted and restricted environments.

At power line frequencies of 50–60 Hz, the magnetic field ERL for the head and torso in unrestricted environments is 0.904 mT (904 μ T), corresponding to a magnetic field strength (H) of 719 A/m. Restricted environments permit higher magnetic limits of 2.71 mT (2710 μ T) and 2.16×10^3 A/m. In comparison, the corresponding limb limits at these frequencies are substantially higher. For example, the magnetic field limit for limbs can reach 63.2 mT at 60 Hz (based on $3790/f$).

Compared with the ICNIRP 2010 guidelines, the IEEE C95.1-2019 standard specifies substantially higher reference levels (allowing higher exposures) for magnetic fields at power frequencies (50/60 Hz) and in the low kHz range. Both standards, however, are intended to prevent the same adverse health effects, despite their differing assessment methodologies. Which standard is applied generally follows local regulations and common industry practice.

3. Review of Related Literature

Our review examines two areas of research to understand EMF exposure in pure EVs and its impact on human health. First, we analyze studies that measured low-frequency EMFs (up to several hundred kHz) inside EVs while they were operating, whether on the road or in test centers. These studies present measurement-based results on the strength, frequency content, and spatial patterns of the fields in the vehicle. This is essential for understanding the actual exposure levels that drivers and passengers may be exposed to. Second, we look at research on the biological and health effects of EMFs within the similar frequency ranges. This helps link the EMF characteristics found in EVs to what they could mean for people's health, based on evidence of how these fields affect the human body.

To identify relevant studies for the review, we searched Google Scholar for peer-reviewed publications. Google Scholar was selected for its broad indexing across both engineering and health literature relevant to our topic. We used specific keywords to narrow down the results best matching our topic and included only English-language articles. Detailed inclusion criteria and search strategies for each of the two reviews are provided in Sections 3.1.1 and 3.2.1, respectively. As a quality check, we selected studies published in journals indexed by the Scimago Journal Rank (SJR), which is a widely recognized system for identifying influential and reliable scientific journals [54]. This approach reflects the scope and intent of a narrative review and may miss some relevant studies or overlook how well each paper was designed. Future researchers can build on our work by searching additional databases, such as PubMed, Scopus, and EMF-Portal, and by using a formal, article-level quality check to formally evaluate each study.

The following sections present each review in turn, beginning with in-vehicle EMF measurements and followed by evidence on the biological and health effects of comparable low-frequency fields.

3.1. EMF Measurements in EVs

3.1.1. Study Identification and Selection for EMF Measurements

We began by reviewing research that measured EMF levels inside EVs. Our search combined three groups of search terms: the vehicle (e.g., vehicle, automobile, automotive, car, EV), the field itself (e.g., magnetic, electromagnetic, frequency, EMF), and the specific focus (e.g., exposure). To keep the results more relevant, we screened for articles with the vehicle and field terms appearing in the title. The full query used was:

exposure (intitle:vehicle OR intitle:vehicles OR intitle:automobile OR intitle:automobiles OR intitle:car OR intitle:cars OR intitle:EV OR intitle:EVs OR intitle:automotive) (intitle:magnetic OR intitle:electromagnetic OR intitle:EMF OR intitle:EMFs OR intitle:frequency OR intitle:frequencies)

Our search covered recent studies published between 1 January 2021, and 31 December 2025. Articles published online in 2025 but assigned to 2026 issues were included to ensure the most current data were analyzed. We screened each study in two steps. We started by checking the title and abstract, and then if a study seemed relevant, we proceeded to a full-text review. We kept only studies that measured EMFs inside pure electric vehicles, excluding all other vehicle types.

3.1.2. Search Results and Included Studies for EMF Measurements

The Google Scholar search returned 515 records using our search query. We excluded 482 articles after applying our criteria and screening titles and abstracts, leaving 33 for a full-text review. In the end, 10 studies met all requirements and were included in our review. Table 2 presents some characteristics of the selected studies, including the authors, testing location, vehicle(s) studied, test environment, measurement instruments, and the frequency range assessed. A detailed discussion of each study follows.

Table 2. Key characteristics of the included studies.

Study	Testing Location (Country)	Vehicle (Make, Model, Year)	Test Environment	Instrumentation	Frequency Range
[55]	Republic of Korea	Hyundai IONIQ, 2016	Real-road driving routes (urban and highway)	NFA 1000 (Gigahertz Solutions) 3-axis for alternating current (AC), Vector/Magnitude Gauss Meter (Alpha Lab) with Hall probe for DC	0 Hz (DC), 16 Hz–2 kHz (AC)
[12]	Italy	Two vehicles of unidentified make, model, and year	Laboratory/chassis dynamometer	Narda EHP-50G analyzer, Narda ELT-400 probe for peak detection	1 Hz–400 kHz (B-field: 25 Hz–2 kHz; WPI: full band)
[56]	China	11 vehicles of unidentified make, model, and year	Not reported	PMM8053B and SMP600 probes	6 Hz–30 MHz
[57]	Romania	Not specified	Real-road driving routes (one free from other electromagnetic disturbances and one near high-voltage power lines)	TriField TF2 handheld meter	40 Hz–100 kHz
[33]	Poland	Not specified	Real-road driving routes (urban)	Metrolab THM1176-MF 3-axis Hall probe for SMF, Narda EFA-300 probe and EMDEX II exposimeter for ELF	0 Hz–32 kHz

Table 2. Cont.

Study	Testing Location (Country)	Vehicle (Make, Model, Year)	Test Environment	Instrumentation	Frequency Range
[58]	Poland	Nissan Leaf, 2021	Real road or test track	Not reported	Not reported
[59]	China	Not specified	Laboratory/chassis dynamometer (for stationary and uniform speed); outdoor closed test track (for acceleration and deceleration)	Narda ELT-400 probe	10 Hz–400 kHz
[19]	Japan	Not specified	Outdoor test course	Narda ELT-400 probe and Eiden 7904A-201 analyzer	1 Hz–400 kHz
[60]	Romania	Not specified	Real-road driving routes (urban)	Maschek ESM-100 H/E Fieldmeter	5 Hz–400 kHz
[52]	India	Four vehicles of unidentified make, model, and year	Real-road driving routes (urban)	HIOKI FT3470-50 3-axis probe	5 Hz–400 kHz

Enegbuma and Kim measured DC and AC extremely low-frequency magnetic fields (ELF-MFs) inside a 2016 Hyundai IONIQ during real-road driving in Republic of Korea [55]. The study evaluated fields at speeds of 40 km/h and 80 km/h as well as during idling and rest using an NFA 1000 m for AC fields (16 Hz–2 kHz) and a Vector/Magnitude Gauss Meter with Hall probe for DC (static 0 Hz). Measurements were taken at 14 locations, including the motor, trunk, and driver, passenger, and rear seat positions. The results showed DC magnetic field levels ranging from 0.66–6 milligauss (mG) at rest to 1.22–6 mG at 80 km/h. For AC fields, the typical ongoing exposure levels ranged from 0.04–0.79 mG at rest to 0.39–8.1 mG at 80 km/h. However, brief AC peak values (transient maximum spikes) ranged from 0.21–6.45 mG at rest to 5.89–199 mG at 80 km/h. The study found that magnetic field levels generally increased with speed, reaching a peak of 199 mG at the front passenger floor during 80 km/h driving, and the floor areas consistently exhibited the strongest fields. However, all measured levels remained below the exposure limits set by ICNIRP and IEEE.

Pinto et al. measured ELF-MFs in two EVs at the European Commission's VeLA-9 electromagnetic compatibility chamber in Italy [12]. EV#1 had a 35.8 kWh battery and 100 kW motor, and EV#2 had a 90 kWh battery and 294 kW motor. Using Narda EHP 50G and ELT 400 probes in the 1 Hz to 400 kHz range, they measured magnetic fields at 19 locations representing the head, thorax, and feet of front and rear occupants and two additional positions in the trunk. The assessment used a 130 s driving cycle consisting of three sequential phases, each involving acceleration, constant-speed driving, and deceleration. Measurements in the 25 Hz to 2 kHz range showed that EV#1 had maximum magnetic flux density (B-field) values of 0.3 to 3.7 μ T, with the highest value of 3.7 μ T recorded at the Rear Thorax Left (RTL) position. The maximum Weighted Peak Index (WPI) ranged from 0.4 to 16.9%, peaking at 16.9% at the Rear Feet Left (RFL) during the cycle. For EV#2, maximum B-field values ranged from 0.1 to 60.4 μ T, with the peak occurring at the Front Feet Left (FFL) during the third acceleration phase. The maximum WPI ranged from 1.3 to 77.0%, and the maximum Exposure Index (EI) ranged from 0.6 to 15.0%, both peaking at the Trunk Right (TR) during the cycle. Despite these peak values, all measured levels remained compliant with international guidelines.

Wang et al. conducted multi-vehicle assessments of EMFs inside eleven anonymous EV models in China [56]. Following the Chinese standard GB/T 37130-2018 with reference to ICNIRP 1998 and 2010 guidelines, they utilized PMM8053B and SMP600 instruments to measure electric and magnetic field strengths across frequency bands of 6 Hz–3 GHz

and 6 Hz–30 MHz, respectively. Testing was performed across 35 interior locations per vehicle, representing the head, trunk, legs, and feet of occupants for driver and passenger seating positions, during constant-speed driving around 40 km/h as well as in stationary and charging modes. Each point was measured five consecutive times with the maximum value retained. Results indicated that most electromagnetic radiation occurred in the 6 to 500 Hz range. Compared to stationary or charging conditions, constant-speed driving produced higher field strengths and more frequent spikes, particularly in the front of the cabin near the powertrain. In the frequency bands up to 100 kHz, magnetic flux density levels were generally below 3.5 μT across modes, with higher values observed in constant-speed driving than in stationary or charging. The maximum electric field strength was 207.78 V per meter in the 6 to 500 Hz band during constant-speed driving, which remained below the ICNIRP reference level. Overall, the study shows that the EVs tested meet the exposure limits at constant speeds, although it does not analyze how those fields change during more dynamic driving situations, such as braking or accelerating.

An investigation by Fotescu et al. [57] compared EMF exposure inside a conventional internal combustion vehicle (Vehicle A) and a battery EV (Vehicle B) of the same class during real-road driving in Romania. They used a TriField TF2 handheld meter placed on the center console to measure AC electric and magnetic fields across a range from 40 Hz to 100 kHz. The study evaluated various conditions including periods with the engine and equipment off or on, acceleration from 0 to 60 km/h, deceleration from 60 to 20 km/h, and fast charging (for Vehicle B). On road sections without external electromagnetic disturbances, Vehicle A produced average magnetic field values of 0.9 to 2.2 mG, while Vehicle B ranged from 1 to 2.3 mG during driving. Electric field levels were highest at 19 V/m in Vehicle A and 8 V/m in Vehicle B when driving. When driving on roads near power lines, magnetic field levels rose slightly in both vehicles. Vehicle A reached 2.3 mG, while Vehicle B reached 2.9 mG. Maximum average electric fields remained consistent, reaching 19 V/m in Vehicle A and 8 V/m in Vehicle B. Even though the EV tended to have higher exposure than the conventional car, all measurements remained within IEEE recommended limits. The study also found that aggressive driving behaviors, such as sudden acceleration, lead to higher emissions compared with smoother, efficient driving.

Gryz et al. measured SMF and ELF-MF levels across multiple types of electric vehicles used in Poland's urban transportation [33]. They examined trams, trolleybuses, buses, and passenger cars, including plug-in electric vehicles (PEVs) with batteries under the cabin and rear DC/AC inverters and AC engines. Using a Narda EFA 300 for MF in the 5 Hz–32 kHz range, an EMDEX II exposimeter for MF in the 40–800 Hz range, and a Metrolab THM1176-MF Hall probe meter for SMF (0 Hz), they took measurements on both the front and rear seats in PEVs during routine driving that included starting, accelerating, driving at constant speeds, braking. The ELF-MF levels in these cars were relatively low compared to larger public transport EVs. Median values ranged from 0.04 to 0.10 μT in the front seats and from 0.17 to 0.30 μT in the rear seats. The highest levels were 0.95 to 1.3 μT in the front and 1.3 to 1.5 μT in the rear. All field levels stayed within the exposure limits for the general public set by Council Recommendation 1999/519/EC. The study also found that exposure to radiofrequency EMF inside the vehicles is mainly due to outdoor mobile network base stations, not to the vehicles' internal systems.

During dynamic driving on roads or test tracks in Poland, Sztarfrowski and Winiarz [58] measured low-frequency magnetic fields inside a 2015 Lexus NX 300H hybrid with two permanent magnet synchronous motors rated at 105 kW on the front axle and 50 kW on the rear axle, as well as inside a 2021 Nissan Leaf EV with a front-wheel-drive 110 kW permanent magnet synchronous motor rated at 110 kW. The testing was performed across all five seats at feet, abdomen, and head heights plus eleven defined cockpit locations

under different dynamic states, such as idling, acceleration from 0 to 50 km/h, constant speeds of 50 km/h, acceleration from 50 to 90 km/h, constant speeds of 90 km/h, braking from 90 km/h to a complete stop, and full acceleration to 90 km/h followed by braking to stop. Although the study does not specify the measurement instruments used or report measurements at specific frequencies, the results showed that B-field values inside the cars were usually strongest in the rear seating area, where the EV often produced higher levels, while the hybrid vehicle occasionally generated the highest peaks in the cockpit. The highest average field measured was 3.24 μT in the EV at head height for the middle rear passenger, and similarly high values were also observed at rear foot level in both vehicles. For maximum single values, the EV reached 4.5 μT at the middle rear passenger's feet, while the hybrid peaked at 4.23 μT at the feet of the rear passenger behind the front passenger seat. In the cockpit, the hybrid produced the strongest average fields between the front seats, with a mean of 3.9 μT and a peak of 5.62 μT . In contrast, the EV's highest value occurred near the left air vent, with a lower mean of 2.15 μT and a lower peak of 2.9 μT .

When analyzing the effects of different driving states, the authors found that at the driver's abdomen, the EV peaked at 2.42 μT at idle and reached 1.92 μT during acceleration from 50 to 90 km/h, while the hybrid's highest value appeared during braking from 90 km/h to a stop. In addition, none of the driver abdominal measurements exceeded 2.5 μT . At the middle rear passenger's abdomen, the EV peaked at 4.43 μT during acceleration to 50 km/h, while the hybrid remained below 2.5 μT across all the tested states. In most conditions, passengers in the rear middle seat were exposed to higher B-field values than the driver. During the test cycle consisting of full acceleration to 90 km/h followed by braking, both vehicles showed similar B-field values at the driver's abdomen during acceleration, but the hybrid reached higher peaks during braking. At the rear middle passenger's abdomen, the EV exceeded the hybrid during late acceleration and early braking, while the hybrid was higher during the remaining periods. Throughout the entire cycle, all measurements stayed below 1.1 μT .

Tan et al. [59] measured low-frequency magnetic fields in a five-seat EV equipped with a 95.7 kWh battery and a 255 kW motor in China using an indoor chassis dynamometer for stationary and uniform speed tests and an outdoor test track for acceleration and deceleration assessments. Utilizing a Narda ELT-400 probe, they evaluated magnetic flux density (B-field) at seven points per seat representing the head, chest, hip, and four positions for the feet of the driver and passengers. Measurements were taken under different driving modes including stationary, uniform driving, acceleration at 2.5 m/s^2 , and deceleration. The measurement results identified acceleration as the mode with the greatest impact on exposure. Maximum B-field values ranged from 0.0047 to 0.1000 μT with the highest of 0.1000 μT at the foot at 680 Hz, 0.0340 μT at the hip, 0.0134 μT at the chest, and 0.0047 μT at the head. Across all the driving modes and seating positions, measured field levels remained well below the public exposure limits specified in GB 8702-2014 and the ICNIRP guidelines.

Fukui et al. [19] measured low-frequency magnetic fields inside current Japanese vehicles in accordance with IEC 62764-1:2022 in a battery EV, a plug-in hybrid electric vehicle, and an internal combustion engine vehicle on a real-road test course in Japan. They used a Narda ELT 400 m and Eiden 7904A-201 frequency analyzer over the 1 Hz to 400 kHz range to record B-field values with a one-second averaging window at IEC-defined locations, including seat surfaces and footwells. Tests covered the stationary mode, driving mode (constant speeds at 40 ± 8 km/h), dynamic mode (acceleration and deceleration from 0 to 90 km/h), and plug-in charging mode. For the EV, they took measurements at nine spots inside the car and three outside, with the probe being placed 6.5 cm from the seat surfaces and 20 cm from other locations. The highest B-field readings were 4.67 μT at the

rear seat during acceleration (4.28 μT during deceleration). At the driver-side dashboard, the peak was 4.39 μT while driving and 4.28 μT while stationary. Readings were consistently higher near the rear seats when the car was moving, which is likely due to the battery pack sitting underneath them. In addition, comparing the current results with previous data, they observed that magnetic field exposure increases with speed. Measurements at the driver's seat rose from 1.38 μT at 10 km/h in earlier tests to 2.51 μT at 80 km/h in the current study. Despite this increase, measurements throughout the study stayed below the reference limits set by ICNIRP for public exposure.

Gliga et al. [60] measured electric and magnetic fields inside an EV in Romania under charging and driving conditions using a Maschek ESM-100 H/E Fieldmeter with a frequency range of 5 Hz to 400 kHz. They measured fields at three locations representing the driver's area, front passenger seat, and rear seat while the vehicle was stationary (0 km/h) and while it was driven at speeds of 50, 75, and 100 km/h. At 0 km/h, electric fields ranged from 0.5 to 1.3 V/m, and magnetic fields ranged from 21 to 93 nanoteslas (nT), or 0.021 to 0.093 μT , with the highest value of 93 nT recorded at the front passenger seat. When the vehicle was driven at 50 km/h, electric fields measured between 0.4 and 1.5 V/m, while magnetic fields increased to 170–520 nT, with the highest level measured at the front passenger seat. At 75 km/h, electric fields ranged from 0.6 to 1.8 V/m, and magnetic fields reached a peak of 422 nT at the front passenger seat. At 100 km/h, electric fields peaked at 2.5 V/m, and magnetic fields reached 987 nT at the rear seat, which was the highest value recorded in the study. Although the study did not compare measurements to specific safety limits, it clearly shows that EMF levels increase with vehicle speed, indicating that higher vehicle speeds produce stronger electromagnetic emissions.

Punniya Murthy and Varadarajan [52] assessed EMF exposure across four different battery EVs during normal city driving in India. The vehicles included two front-wheel-drive models (EV1 and EV3) and two rear-wheel-drive models (EV2 and EV4) with different power outputs. They assessed exposure at locations near the leg, torso, head, dashboard, rear seat, and chassis, using an ETS-Lindgren HI-3638 electric field meter and a HIOKI FT3470-50 three-axis magnetic field tester operating in the 5 Hz to 400 kHz range. EMF levels were measured while driving in the city with changing speeds, acceleration, and braking. Measurements for EV1 showed maximum B-field values ranging from 0.25 to 1.92 μT with the peak recorded at the leg position. For EV2, B-field values ranged from 0.28 to 1.6 μT and peaked at the dashboard position, while EV3 exhibited values between 0.2 and 1.75 μT with the maximum observed at the leg position. EV4 showed exposure levels ranging from 0.4 to 0.98 μT , with a peak also observed at the leg position. Regarding E-field strength, peak levels were recorded at 137 V/m in EV1 (leg), 69 V/m in EV2 (dashboard), 97 V/m in EV3 (leg), and 53 V/m in EV4 (torso). The authors found that the highest field levels tended to occur in the leg and dashboard areas. They attributed this to the proximity of power flow between the motor and other drive components when the vehicle accelerates or brakes. Overall, the measured EMF levels stayed within the safety limits recommended by ICNIRP and IEEE.

Table 3 synthesizes the findings across the included studies, summarizing the driving modes and measurement positions used, the magnetic field levels reported, and the maximum values reported for each study.

Table 3. Summary of measurement protocols and reported exposure levels from the included studies.

Study	Driving Mode	Measurement Locations	Reported Levels	Highest Exposure
[55]	Rest, idling, constant speed 40 km/h, constant speed 80 km/h	14 points: Head, chest, and feet regions for front and rear seats plus motor and trunk	DC field: 0.066~0.6 μ T at rest, 0.063~0.733 μ T while idling, 0.08~0.6 μ T at 40 km/h, and 0.11~0.81 μ T at 80 km/h. AC field: 0.004~0.079 μ T at rest, 0.011~0.221 μ T while idling, 0.026~0.24 μ T at 40 km/h, and 0.039~0.81 μ T at 80 km/h. AC peak field: 0.021~0.645 μ T at rest, 0.033~0.494 μ T while idling, 0.2~0.882 μ T at 40 km/h, and 0.589~19.9 μ T at 80 km/h.	19.9 μ T (AC peak) near passenger floor during 80 km/h
[12]	130 s cycle: acceleration, constant speed, deceleration	19 points: head, thorax, feet for front and rear seats, plus trunk left/right	Max: 0.3~3.7 μ T in EV#1 (peak at Rear Thorax Left, RTL, during acceleration) and 0.1~60.4 μ T in EV#2 (peak at Front Feet Left, FFL, during acceleration).	EV#1: 3.7 μ T at rear thorax left (RTL) during acceleration EV#2: 60.4 μ T at front feet left (FFL) during acceleration
[56]	Stationary and constant speed 40 $\pm$ 8 km/h	35 points: head, trunk, legs, and feet for front and rear seats	Generally below 3.5 μ T for frequencies 6 Hz to 100 kHz across modes	Highest levels observed mainly at the front passenger foot area during 40 $\pm$ 8 km/h
[57]	Engine off, engine on (equipment off), engine on (equipment running), acceleration 0~60 km/h, deceleration 60~20 km/h	Center console	Average: 0.1~0.23 μ T (clean road) and 0.2~0.29 μ T (disturbed road).	0.3 μ T during acceleration (disturbed road)
[33]	Starting, accelerating, constant speed, braking	Front/rear seats	Median: 0.04~0.10 μ T in the front seats and 0.17~0.30 μ T in the rear seats. Maximum: 0.95~1.3 μ T in the front seats and 1.3~1.5 μ T in the rear seats.	1.5 μ T in the rear seats
[58]	Idling, acceleration 0~50 km/h, constant speed 50 km/h, acceleration 50~90 km/h, constant speed 90 km/h, braking 90~0 km/h, full acceleration to 90 km/h followed by braking to complete stop	Head, abdomen, and feet for front and rear seats, plus 11 points in cockpit.	Highest mean field: 3.24 μ T at the rear middle passenger head; Highest peak field: 4.5 μ T at the rear middle passenger feet; Highest cockpit mean: 2.15 μ T near the left air vent; Highest cockpit peak: 2.9 μ T near the left air vent; Driver abdomen peak: 2.42 μ T at idle; 1.92 μ T during acceleration from 50 to 90 km/h; all values < 2.5 μ T; Rear middle passenger abdomen peak: 4.43 μ T during acceleration to 50 km/h; Full acceleration to 90 km/h with braking: all values < 1.1 μ T	4.5 μ T at the rear middle passenger feet
[59]	Stationary, uniform speed, acceleration, deceleration	7 points per seat: head, chest, hip, and 4 foot points for front and rear seats	0.0047 (at 120 kHz)~0.1 μ T (at 680 Hz) at foot, 0.0046 (at 120 kHz)~0.034 μ T (at 680 Hz) at hip, 0.0043 (at 120 kHz)~0.0134 μ T (at 680 Hz) at chest, and 0.0034 (at 120 kHz)~0.0047 μ T (at 680 Hz) at head during acceleration.	0.1 μ T at driver foot during acceleration at 680 Hz
[19]	Stationary, constant speed 40 $\pm$ 8 km/h, acceleration/deceleration 0~90 km/h	Seat surfaces, footwells, dashboard, exterior locations	Max: 4.28 μ T while stationary (driver-side dashboard), 4.39 μ T while constant speed (driver-side dashboard), 4.67 μ T during acceleration (rear seat), 4.28 μ T during deceleration (rear seat).	4.67 μ T at rear seat during acceleration
[60]	Stationary and constant speeds (50, 75, 100 km/h)	Front/rear seats	Max: 0.093 μ T at 0 km/h (front passenger seat), 0.52 μ T at 50 km/h (front passenger seat), 0.422 μ T at 75 km/h (front passenger seat), 0.987 μ T at 100 km/h (rear seat).	0.987 μ T at rear seat during 100 km/h
[52]	Usual city driving conditions	Leg, torso, head, dashboard, rear seat, chassis	Max: 0.25~1.92 μ T in EV1 (peak at the leg position), 0.28~1.6 μ T in EV2 (peak at the dashboard), 0.2~1.75 μ T in EV3 (peak at the leg position), 0.4~0.98 μ T in EV4 (peak at the leg position).	1.92 μ T at the leg position in EV1

3.1.3. Analysis of the Included Studies

The selected studies provide measured evidence on EMF exposure inside EVs from diverse geographic areas, spanning Republic of Korea, Italy, China, Romania, Poland,

Japan, and India. This global interest shows that measuring EMFs inside EVs is seen as important for understanding possible health effects as more people start using them. However, the studies vary widely in how they are conducted, including the vehicles tested, the equipment used, which frequencies were measured, where measurements were taken, and how the vehicles were driven.

The number of vehicles tested was different across studies. Some studies focused on a single, specific car model, while others evaluated groups of vehicles, testing up to 11 vehicles in a single study. The measuring equipment varied in both type and capability, except in a study by Sztafrowski and Winiarz [58], which did not report what instrumentation they used. Across the studies, the measured frequencies ranged from 0 Hz to 30 MHz. While most research focused on low frequencies (1 Hz to 2 kHz), fewer studies tested intermediate frequencies (2 kHz to 100 kHz), and only a single study [55] actually measured static magnetic fields (0 Hz). Testing environments differed from laboratory dynamometers and outdoor tracks to actual urban and highway driving. Each environment affects the measurements differently. Studies done on real roads capture the fields that passengers actually experience in the vehicle, but they can be affected by outside EMFs from the surrounding environment. Fotescu et al. [57] explicitly addressed this by choosing routes without external electromagnetic disturbances. Conversely, laboratory tests give researchers more control and make results easier to repeat, but they may not reflect real driving. This difference can affect how the motor and electrical parts operate and change the resulting EMF emissions. The measurement locations selected across studies include the head, chest, abdomen, legs, and feet for both front and rear seats, as well as the trunk, the dashboard area, and in some cases the vehicle exterior or chassis. Though individual studies used different measurement points, the available evidence shows how field strength varies across cabin locations and body regions. There were also variations in how the cars were driven during the tests. Several studies measured vehicles during idling and constant speeds, some included acceleration and deceleration, and others tested a complete driving cycle of idling, accelerating, braking, and stopping, which covers EMF exposure during both low-power driving and high-power periods that are expected to generate stronger magnetic fields.

The included studies report magnetic field levels in either microtesla (μT) or milligauss (mG), which can be directly converted ($1 \text{ mG} = 0.1 \mu\text{T}$). After converting all results to μT for comparison, the majority of reported exposure levels range from 0.01 to 5 μT , with the maximum reaching around 60 μT . The general consistency of reported field levels across studies conducted in different countries, with different instruments, and on different vehicles lends some support to the overall exposure pattern. Moreover, although individual studies measured different specific points, the combined findings show that the highest reported field levels were often found at or near the floor and footwell and the levels decreased at higher body positions. Pinto et al. [12] observed peak values of 60.4 μT at the front left foot area in one vehicle. Tan et al. [59] also identified the driver's foot area as a hotspot, and Punniya Murthy and Varadarajan [52] found the leg position to be the highest exposure location across all four vehicles they studied. This pattern is expected given that the floor and footwell areas are closest to the motor, cables, and battery.

Another finding is that rear seat passengers face field levels that are similar to, or in some cases higher than, those measured in the front seats. Gryz et al. [33] reported higher field levels at rear seat positions, with medians of 0.17 to 0.30 μT and maximums of 1.3 to 1.5 μT , compared to front seat medians of 0.04 to 0.10 μT and maximums of 0.95 to 1.3 μT . Adding to this pattern, Pinto et al. [12] observed a peak of 3.7 μT at the rear seat in one vehicle during acceleration, Fukui et al. [19] recorded a rear seat peak of 4.67 μT during acceleration, and Gliga et al. [60] identified the rear seat at 100 km/h as the highest

exposure location in their study. This may relate to vehicle architecture, since in many EVs the battery pack extends under the rear passenger floor, placing rear occupants closer to one of the vehicle's main sources of EMF than those sitting in the front.

The reviewed evidence also reveals that driving modes are associated with differences in field levels. Across many studies, the highest field levels are reported during acceleration and higher-speed driving, likely reflecting the high motor current demanded during both phases. During vehicle acceleration, Fotescu et al. [57] found a maximum of 3 mG (0.3 μ T) on a disturbed road, Sztafrowski and Winiarz [58] reported the highest reading of 4.43 μ T at the rear passenger abdomen (0 to 50 km/h), and Fukui et al. [19] recorded values up to 4.67 μ T at the rear seat. Pinto et al. [12] also observed peak levels during acceleration in the two vehicles they studied. At constant higher speeds, Enegbuma and Kim [55] recorded AC fields reaching 199 mG (19.9 μ T) near the passenger floor at 80 km/h, while Gliga et al. [60] reported a peak of 0.987 μ T at the rear seat at 100 km/h.

Overall, the reviewed studies indicate that occupants of EVs are exposed to a complex and continuously evolving electromagnetic environment. While the field levels tend to be low to moderate under most driving conditions, they can spike in specific areas, particularly near the floor and during dynamic driving such as acceleration or deceleration. In spite of this variability, all studies that compared their results to a safety standard found compliance with the applicable limits, whether set by ICNIRP, IEEE, or a national standard derived from them.

3.1.4. IEC 62764-1 and Its Adoption in EV Magnetic Field Studies

The International Electrotechnical Commission's IEC 62764-1:2022 is the first standard that establishes how to measure low-frequency magnetic fields inside vehicles. It applies to passenger cars and light commercial vehicles, covering internal combustion engine vehicles, electric vehicles, and hybrid electric vehicles. The standard covers the frequency range from 1 Hz to 100 kHz and applies to electric vehicle supply equipment and associated cables. However, the scope excludes wireless power transfer equipment, charging stations, and any magnetic field transients lasting less than 200 ms.

Testing is conducted across four different modes that consist of stationary, constant-speed driving (40 ± 8 km/h), dynamic (acceleration and deceleration), and plug-in charging. Measurements are required in all accessible regions (cabin, cargo, powertrain, and exterior) and must be performed in controlled environments where ambient magnetic field exposure is less than 10 percent of applicable limits, using either a dynamometer or an outdoor track ($\pm 2\%$ slope). Additionally, to ensure consistent results, the standard provides detailed guidance on adjusting the seats, headrests, steering wheel, and seat-back. It also specifies measurement zones corresponding to body areas such as the feet, trunk, head, and hands. Slow scans are conducted within these zones using a probe with a maximum sensor area of 100 cm², while maintaining the probe center at a distance of 6.5 cm from seat surfaces and 20 cm from all other surfaces, in order to locate and record the maximum magnetic field exposure.

Because measurement accuracy is critical, the standard also requires calculations of potential measurement errors based on the probe's calibration, positioning, and performance. A ten percent margin of error is included to account for uneven magnetic fields. To ensure the test can be repeated and the results compared, the test report must include details such as measurement locations, speeds, battery charge levels, and any departures from the recommended settings.

Across the studies included in our review, most papers do not state that measurements were performed in accordance with IEC 62764-1. A smaller number of studies used methods closer to the IEC standard but did not state that they formally complied. Pinto et al. [12]

explicitly referred to the earlier IEC technical specification and applied a customized, pre-normative measurement procedure. Tan et al. [59] cited IEC 62764-1 and incorporated many elements of its methodology, but the study does not indicate formal compliance with the standard. Wang et al. [56] did not use IEC 62764-1 but instead followed GB/T 37130-2018, a formal Chinese standard for measuring magnetic fields in vehicles that closely aligns with the IEC framework. Outside of these studies, Fukui et al. [19] is the only work that clearly states it adopted IEC 62764-1.

To improve the quality and comparability of future EV magnetic field research, studies should adopt the measurement framework described in IEC 62764-1. In the absence of a common standard, different studies make different choices about probe models and sizes, methods for processing data, and definitions of what constitutes driving modes. These differences make it very difficult to compare findings across studies or to draw broader conclusions. It would also be very helpful if researchers clearly reported how they calibrated their instruments, how they positioned their probes, and what settings they chose, because these factors can materially affect measured values. In addition, sharing raw time series measurements or complete frequency information would give other researchers the ability to reprocess the data and evaluate the results in a consistent way.

3.2. Biological and Health Effects of Low-Frequency EMF Exposure

3.2.1. Study Identification and Selection

We next reviewed research on the biological and health effects of exposure to EMF within similar frequency ranges. Our search combined three groups of search terms: the exposure context (e.g., exposure, low frequency), the potential health outcome (e.g., health, safety, risk, disease, cancer), and the field term (e.g., magnetic, electromagnetic, frequency, EMF). This ensured the relevance of the retrieved literature by screening for articles where the field types and health-related terms appeared specifically in the title. The query used was as follows:

exposure ("low frequency" OR "low frequencies") (intitle:health OR intitle:safety OR intitle:risk OR intitle:risks OR intitle:hazard OR intitle:hazards OR intitle:symptom OR intitle:symptoms OR intitle:disorder OR intitle:disorders OR intitle:disturbance OR intitle:disturbances OR intitle:disease OR intitle:diseases OR intitle:sickness OR intitle:sicknesses OR intitle:cancer OR intitle:cancers) (intitle:magnetic OR intitle:electromagnetic OR intitle:EMF OR intitle:EMFs)

For this second phase of the review, we restricted our search to studies published between 1 January 2024, and 31 December 2025. We applied the same inclusion criteria and screening process described in the previous phase.

3.2.2. Search Results and Included Studies

Our initial Google Scholar search generated a total of 400 records. After applying the eligibility criteria and screening titles and abstracts, 376 articles were excluded, leaving 24 for a full-text review. Ultimately, we found 10 studies that met all inclusion requirements. Table 4 summarizes the key characteristics of the selected studies, including the authors, country, study design, population, exposure source, and health outcome examined. These studies are discussed individually in detail below.

Table 4. Key characteristics of the selected studies.

Study	Country	Study Design	Population	Exposure Source	Health Outcome Examined
[61]	Finland	Cohort study	8840 exposed; 179,285 referents; 52,599 additional comparison group	Residential 50 Hz exposure from indoor transformers	Adult cancer incidence

Table 4. *Cont.*

Study	Country	Study Design	Population	Exposure Source	Health Outcome Examined
[62]	Russia	Diagnostic model development	Power plant workers; 100 healthy students; 100 cardiac patients	Occupational 50 Hz exposure estimated using calculated variables (no direct measurements)	Heart rhythm disorders and nervous system diseases
[63]	Russia	Diagnostic model development	200 power industry workers (100 at risk; 100 healthy)	Occupational 50 Hz exposure via composite index (no direct measurements)	Immune system diseases
[64]	Italy	Case–control study	182 childhood leukemia cases (0–14 yrs, 1998–2019); 726 controls	Residential proximity to transformer stations (50 Hz); exposed if within 15 m or 25 m (no direct measurements)	Childhood leukemia
[65]	Slovakia	Laboratory experimental study	Bakery yeast and human macrophages	Lab exposure at 20 μ T (typical urban EMF levels) at 50 Hz and combined 50 + 150 Hz	Yeast growth/metabolism/survival/protein composition; Macrophage phenotype/morphology/behavior
[66]	Republic of Korea	Cross-sectional study	85 adults (20–60 yrs) (factory workers vs. low-exposure workers)	Occupational exposure in factory settings	Blood pressure, heart rate, and sleep quality
[67]	Mexico	Autopsy-based laboratory study	34 individuals (9 children, 25 adults); 164 brain tissue samples	Environmental magnetic particles in brain tissue exposed to magnetic fields in lab	Brain cell damage and neurological disease markers
[68]	Mexico	Case–control study	200 children with CNS tumors (2017–2022); 793 controls	Residential exposure (30–800 Hz) measured in bedroom	Childhood CNS tumors
[69]	Finland	Cohort study	5652 exposed; 115,772 referents; 34,138 additional comparison group	Residential 50 Hz exposure from indoor transformers	Alzheimer’s disease
[70]	France	Case control study	4117 childhood acute leukemia cases (<15 yrs, 2002–2010); 44,838 controls	Residential exposure from 63–400 kV overhead power lines	Childhood acute leukemia

Juutilainen et al. [61] conducted a study looking at cancer risk from residential exposure to magnetic fields. The study population was Finnish adults living in apartment buildings, split into those living near indoor electrical transformer stations and those who did not. The data were drawn from a database of residential buildings containing indoor transformer stations. In total, they followed 8840 people classified as exposed who had lived in ground floor or first floor apartments directly adjacent to the transformer room and 179,285 people living on upper floors of the same buildings served as the referent group. A third group of 52,599 people living on the ground and first floors, but not next to the transformer room, was included to distinguish between EMF effects and other factors related to living on lower floors. Exposure was assessed based on apartment location relative to the transformer room, which produces 50 Hz ELF-MFs, rather than personal measurements. The study tracked various types of adult cancer, with emphasis on overall cancer risk and specific cancers such as cancers of the digestive organs, gallbladder, and testis. They used standardized incidence ratios (SIR) with 95% confidence intervals calculated from the Finnish Cancer Registry to compare observed cancer cases in the exposed group against what would be expected based on the cancer rates in the referent group. Overall, the study found no increase in cancer rates. However, the exposed group did show a statistically significant increase in digestive organ cancers, with especially large increases for gallbladder cancer and small intestine cancer. Notably, the comparison group living on the same lower floors but away from transformer rooms showed no such increase. This suggests that the increased risk is related to EMF exposure rather than simply living on lower floors. The authors also described the study’s weaknesses. For example, they lacked

individual data on smoking, diet, and other personal confounders, though they think these probably do not differ much between people living next to transformer rooms and others in the same building. Data on occupational EMF exposure were also missing, and this might have affected the results.

Korenevskiy et al. [62] developed a fuzzy-based bioengineering system to predict and detect nervous system diseases and heart rhythm problems in electric power workers, who are regularly exposed to 50 Hz EMFs on the job. The study population included power plant workers as well as two comparison groups of 100 healthy university students and 100 patients with existing heart conditions. The study is not designed to demonstrate that EMF causes disease. It focuses on building and validating a diagnostic model and therefore relies on earlier research that already links long-term industrial EMF exposure and other workplace risk factors, such as noise, chemical exposure, and psychological stress, to nervous system problems. Additionally, rather than measuring EMF exposure directly for each worker, the authors estimated exposure levels using calculated variables. The diagnostic model they developed performed well in their test samples, correctly identifying disease with 98% sensitivity and 96% specificity, and showing high confidence in early-stage detection. However, the study did not report conventional epidemiological measures such as *p*-values for population-level risk. The authors concluded that exposure to 50 Hz EMFs is a major risk factor for nervous-system and heart-related diseases in power workers, particularly when it occurs along with other risks such as psycho-emotional stress. They also noted that their study had several limitations, including that the tool depends heavily on expert input, environmental risk factors were not fully modeled, and the dataset was small given the complexity of the data.

A closely related paper by the same research group, Korenevskiy et al. [63], examined a different health domain and target outcome in a separate article, shifting from nervous system disorders to immune system diseases in electric power industry workers. The study included workers from various power companies in Russia, such as thermal, nuclear, and hydroelectric plants. To validate their model, the authors tracked 200 people over five years (2014–2018), including 100 considered at risk for immune disease and 100 healthy. Similarly, the study did not test whether EMF causes disease but instead focused on developing and testing a diagnostic model, therefore relying on prior research that already associates long-term occupational exposures, including EMFs, noise, chemicals, and psychological stress, with immune system disorders. Also, rather than directly measuring individual EMF exposure, they used a composite measure of field strength and years on the job, with risk assumed to increase after about three to five years. The models also included other factors that might affect immune health, such as lifestyle and medical history, and indicators of oxidative status. The model's prediction accuracy, measured by sensitivity and specificity, was generally 0.85 or higher, reaching about 0.95 for early detection, and these measures improved over time and then stabilized. It was concluded that exposure to 50 Hz EMFs is an important occupational risk factor for immune system disease in power workers. The authors also pointed out a number of limitations, including reliance on expert judgment due to a lack of large, labeled datasets, difficulty separating the impact of EMFs from other exposures, no direct measurements of individual exposure, and limited applicability outside the power industry.

Malavolti et al. [64] investigated if residential exposure to magnetic fields from electrical transformers is linked to an increased risk of childhood leukemia. The study took place in two provinces in northern Italy, Modena and Reggio Emilia, with about 1.3 million people. It looked at 182 cases of childhood leukemia diagnosed between 1998 and 2019 in children aged 0–14. These were compared with 726 similar children without leukemia, matched by sex, birth year, and where they lived. On average, children were

diagnosed with leukemia at about 6.2 years old and 6.3 years for the specific subgroup with acute lymphoblastic leukemia. Exposure was not assessed using personal measurements but instead employing a geographical information system. The authors used a regional environmental database to identify 13,434 transformer stations near residential buildings in the two provinces. Then they mapped both the stations and the participants' homes and defined exposure as living within 15 or 25 m of a station. Children who lived outside these ranges were considered unexposed. These thresholds came from prior research showing that apartments above or adjacent to these stations can have magnetic fields of 0.3–1 μT , around 10–20 times higher than background residential levels and in the same range linked to higher leukemia risk in the literature. They estimated the risk of childhood leukemia by distance to transformer stations using odds ratios with 95% confidence intervals. They ran conditional logistic regression models that controlled for matching factors (sex, birth year, and province of residence) and other potential variables, including air pollution, proximity to high-voltage power lines, nearby petrol stations, urban area density, and nearby crop density as a proxy for pesticide exposure. Overall, the study found no significant link between living near transformer stations and childhood leukemia. The results were similar regardless of whether a 15 m or 25 m distance was used, showing no evidence of increased risk, although the estimates were slightly higher among children aged five years and older, suggesting a possible but weak increase in risk. The study's limitations included the small number of exposed children, lack of information about where the children spent their time, and missing personal details, such as radiation exposure history, early life nutrition, or family health, despite adjusting for environmental factors.

Sincak et al. [65] conducted a laboratory study comparing how low-level EMFs, similar to those found in daily environments, affect two different model organisms, bakery yeast and human macrophages. They aimed to determine which of these commonly used test organisms better predicts human health risks from urban EMF exposure. The study tested two types of magnetic field exposure designed to reflect typical urban EMF levels. One was a simple 50 Hz magnetic field, called M50. The other combined 50 Hz and 150 Hz magnetic fields, called M50/150. Both were set to 20 μT , similar to field levels from household appliances and power lines. The magnetic fields were generated using a specially designed copper coil system supplied by a signal generator. The background control condition was the natural geomagnetic field measured in the laboratory at approximately 50 μT . The two model organisms were exposed for different durations. The yeast cells were exposed to each field condition for 24 h, followed by a 24 h recovery period in normal laboratory conditions, whereas the macrophages were exposed for two hours, then monitored continuously for 24 h. The health outcomes examined in yeast included growth rate, metabolism, whether the cells survived, and protein composition. For macrophages, the authors were mainly interested in immune cell phenotypes, especially changes in cell shape and behavior. The results were very different in the two test organisms. In yeast, neither the M50 field nor the M50/150 field caused statistically significant changes in pH, growth, cell survival, or protein composition. In macrophages, however, the effect happened quickly and strongly. After just 2 h of exposure to either field condition, the anti-inflammatory cells changed shape and behaved like pro-inflammatory cells. This change lasted about 12 h and then the cells slowly returned to their usual shape within 24 h, suggesting the effect was temporary. The authors pointed out that this kind of change has usually been seen only with very strong magnetic fields such as those in MRI machines. Seeing it at these much weaker levels could be important and concerning. The study had several limitations. For yeast, the experiments were limited in scope, and the fields may be below the level needed to detect subtle effects. For macrophages, the study only looked at changes in cell shape, not at tests

that would show whether the cells were actually becoming inflammatory, and because exposure lasted just 2 h, the impact of longer or repeated exposure remains unknown.

Weerasinghe et al. [66] studied whether working in environments with higher ELF-MF levels is connected to problems with blood pressure, heart rate, and sleep quality. The study involved 85 adults between 20 and 60 years old, divided into high exposure factory workers and a low-exposure group of agricultural, office, service, and academic workers. Participants wore a dosimeter on their body for 24 h to measure exposure to ELF-MF. For analysis, exposure measurements were split into work and sleep periods. It was found that factory workers had significantly higher average exposure to ELF-MF both during work and sleep compared to the general group. For health outcomes, the authors measured systolic blood pressure, diastolic blood pressure, and heart rate four times during work and then calculated an average. They monitored sleep over one night using an Apple Watch for measuring total sleep time and sleep stages. The results showed that factory workers, who had higher exposure, had significantly higher systolic blood pressure than the general group (127.91 ± 8.78 vs. 123.37 ± 9.94 mmHg), while diastolic blood pressure and heart rate were not significantly different between groups. For sleep, factory workers had significantly shorter deep sleep duration than the general group (58.12 ± 28.95 vs. 75.93 ± 31.02 min), while total sleep duration did not differ significantly. Overall, the findings indicate that higher ELF-MF exposure may negatively affect blood pressure and sleep quality. The authors acknowledged several limitations. These include the use of an Apple Watch rather than polysomnography for sleep assessment, potentially lowering accuracy, as well as the small number of participants and the difficulty of separating ELF-MF effects from other influences, such as stress and noise, which may affect blood pressure and sleep.

A 2025 study led by Calderón-Garcidueñas et al. [67] examined whether tiny magnetic particles from air pollution accumulated in the human brain would physically move and cause damage within brain tissue when exposed to magnetic fields. They analyzed brain tissue from 34 people, including both children and adults in Mexico City who were seemingly healthy at the time of death from non-neurological causes such as accidents or homicide. A total of 164 brain tissue samples were obtained from 9 children with an age of 12.8 ± 6.4 years and 25 adults with an age of 35.4 ± 21.9 years. The people studied had been breathing polluted air from Mexico City for most of their lives. This air had high levels of tiny pollution particles (PM 2.5), such as ultrafine particulate matter (UFP) and industrial nanoparticles (NPs), that consistently exceed US EPA standards. The authors analyzed the number of magnetic particles in different brain regions that control important body functions and exposed these tissue samples to magnetic fields in the laboratory. They applied magnetic fields of different strengths and directions to the brain samples and tracked how the particles responded. It was found that the particles were damaging brain cells by breaking down their internal structures. Most concerning is that these particles move around when exposed to weak magnetic fields similar to those found in everyday environments, which could make the damage worse. Additionally, every sample they examined showed early signs of diseases usually seen in elderly people, such as Alzheimer's, Parkinson's, and others. The study also suggests that these ferrimagnetic particles may contribute to a range of health problems including depression, sleep problems, memory issues, and neurological diseases. One limitation noted by the authors is that because the study relied on autopsy data, it was not possible to track participants over time or directly measure their sleep quality, cognitive function, or autonomic function. Health outcomes were therefore inferred using brain samples and earlier research. Also, the study group was almost all male, so the findings may not fully apply to women. Additionally, because the subjects were exposed to a mix of different pollutants and EMFs, it is impossible to determine which caused specific effects.

Correa-Correa et al. [68] researched whether exposure to ELF-MF and radiofrequency radiation is associated with central nervous system (CNS) tumors in children, based on data collected in Mexico City between 2017 and 2022. The study group was made up of 200 children who had CNS tumors and 793 who did not. The study measured residential ELF-MF exposure by placing a meter (EMDEX II) in the child's bedroom for 24 h during the year prior to the child's diagnosis or interview. The meters recorded readings every four seconds and captured magnetic fields in the 30 to 800 Hz range. The authors averaged all those readings and compared children with average exposure levels below 0.1 μT to those with higher levels. The statistical analysis showed that children exposed to magnetic fields of 0.4 μT or higher had a significantly increased risk of developing CNS tumors. An analysis of different age groups showed that this risk was especially high in children aged 11 and older. The authors pointed out several limitations. Specifically, a single 24 h measurement in the bedroom might not accurately represent long-term exposure. They also did not have data on external factors such as how close homes were to power lines or what appliances were in use. Other issues were that using hospitalized children as controls might not represent typical children in the general population and the small sample size prevented the researchers from analyzing specific types of tumors.

Liimatainen et al. [69] investigated the relationship between Alzheimer's disease and residential exposure to ELF-MFs from indoor transformer stations in Finland. They used a specialized database called DaFBITS to identify 155,562 people who lived in apartment buildings that contained indoor transformer stations operating at 50 Hz. The exposed group included 5652 people who lived right above or next to a transformer room for at least 6 months. The rest 115,772 people who lived on higher floors of the same buildings served as the comparison group. To separate the effect of floor level from transformer exposure, the study also included a separate group of 34,138 who lived on the first or ground floor but not next to a transformer room. Of the 155,562 people in the study, about 47% were men and 53% were women, and the median duration of residence ranged from 3.9 to 4.4 years across apartment categories. The authors referred to earlier measurements from 30 buildings, which reported average magnetic field levels of about 0.56 μT in the exposed group, about 0.21 μT in other units on the lowest floor, and about 0.10 μT in the reference group on the higher floors. The study identified 3663 cases of Alzheimer's disease, which included 123 in the exposed group and 2810 in the reference apartment group, using the databases of Finland's Drug Purchase Register and Drug Reimbursement Register, with 1 January 1999 as the earliest possible diagnosis date. It was ultimately concluded that living near transformer stations and being exposed to ELF-MF was not associated with an increased risk of Alzheimer's disease. The authors highlighted multiple limitations in their work. First, they did not account for magnetic field exposure from sources other than transformer stations such as household appliances or possible workplace exposure. Second, they lacked information on individual factors, such as genetics and diet that may affect Alzheimer's disease risk. Lastly, some Alzheimer's cases may have been wrongly classified in the databases, and exposure measures based on apartment location, instead of personal exposure measurements, may not reflect the actual exposure levels.

Mancini et al. [70] conducted a case-control study investigating whether childhood acute leukemia risk in France is associated with residential exposure to ELF-MFs from high-voltage overhead power lines. The study compared children under the age of 15 years with acute leukemia to similar children without the disease across mainland France except Corsica from 2002 to 2010. The sample included 4117 acute leukemia cases and 44,838 contemporary controls representative of the French pediatric population. Exposure was assessed in two ways. First, the authors measured how close each children's home was to the nearest 63–400 kV overhead line (HVOL), grouping those within 1000 m into

>600 m, 200–599 m, 100–199 m, 50–99 m, and <50 m. Second, magnetic field exposure was modeled at each address using EFC400 software and expert input, accounting for a line's voltage, average current intensity, configuration, cable characteristics, pylon height and location, and the altitude, with results grouped into <0.1 μ T, 0.1 to <0.3 μ T, and $\geq$ 0.3 μ T (and $\geq$ 0.4 μ T for comparison with earlier studies), while additional sensitivity analyses were run to evaluate geocoding error and potential confounders. The study found contrasting results between distance-based and magnetic field-based exposure measures and therefore provided mixed evidence. For children under 5, living within 50 m of an overhead power line was associated with an increased risk of acute leukemia, with an odds ratio of 1.6 and a 95 percent confidence interval from 1.0 to 2.7, especially when the analysis was limited to addresses with the best location accuracy. Conversely, no association was observed with calculated magnetic field levels, and the findings were consistent across different sensitivity analyses. The authors pointed out some limitations, including very few children with high magnetic field exposure, inconsistent address accuracy, and possible exposure misclassification due to the rapid decline in magnetic fields with distance from power lines. They also lacked residential history, exposure duration, and individual socioeconomic data, and in some cases, magnetic field estimates could not be calculated because of complex power line configurations or unavailable regional data.

Table 5 summarizes the included studies by health domain and key findings, indicating whether EMF exposure was linked to adverse health outcomes, biological effects, or no significant association.

Table 5. Summary of key findings from the selected studies.

Study	Health Domain	Key Findings
[61]	Cancer	No overall increase in cancer risk; statistically significant increase in digestive-organ cancers among those living adjacent to transformer rooms
[62]	Cardiovascular health	EMF identified as a major occupational risk factor for heart disorders and nervous system, especially combined with psycho-emotional stress
[63]	Immune system health	EMF identified as an important occupational risk factor for immune system disease
[64]	Childhood cancer	No significant link between living near transformer stations and childhood leukemia, despite a slightly higher risk among children aged five and older.
[65]	Cellular and immune responses	No significant effects in yeast; macrophages rapidly shifted to a pro-inflammatory phenotype after 2 h of exposure at 20 μ T and reversed within 24 h, suggesting that everyday EMF exposure may temporarily affect human immune cell shape and behavior.
[66]	Cardiovascular health and sleep	Higher exposure linked to higher systolic blood pressure and shorter deep sleep, but not to diastolic blood pressure or heart rate.
[67]	Neurological health	Magnetic particles in brain tissue moved under weak magnetic fields, associated with cellular damage and early signs of neurological disease.
[68]	Childhood cancer	A significant link between exposure at $\geq$ 0.4 μ T and a higher risk of CNS tumors, particularly in children aged 11 and older.
[69]	Neurological health	No significant link between living adjacent/above transformers and Alzheimer's risk
[70]	Childhood cancer	Living within 50 m of overhead power lines linked to increased acute leukemia risk in children under five; no association found using calculated magnetic field levels

3.2.3. Analysis of the Selected Studies

The ten reviewed studies span seven countries, illustrating that low-frequency EMF health research is being conducted across multiple countries and settings. Finland contributed two cohort studies, both from research groups with strong experience in residential EMF research. Russia contributed two studies on diagnostic model development, focusing on occupational exposure in power plants. Italy, Slovakia, Republic of Korea, and France

each contributed one study, while Mexico contributed two studies from separate research groups examining different health outcomes.

The sources of EMF exposure vary across the reviewed studies, spanning typical residential and occupational environments such as transformer stations, power lines, bedroom fields, and industrial workplaces. Alternatively, some researchers simulated exposures in a controlled laboratory setting or focused on the magnetic particles already present in human brain tissue. This variety of sources provides evidence across a wide range of exposure conditions.

The reviewed studies cover four broad health domains, including cancer, neurological health, cardiovascular health and sleep, and cellular and immune responses. Four studies examined cancer, with two focusing on childhood leukemia, one on childhood nervous system tumors, and one on adult cancer. Two studies addressed neurological health, with one examining Alzheimer's disease and the other neurological disease markers in brain tissue. These diverse outcomes reflect the current scientific view that exposure to low-frequency magnetic fields may be relevant to multiple biological systems.

The findings across the four domains show a mixed pattern, which likely reflect both the complexity of EMF effects in the body and the differences in study designs and populations. In the cancer domain, some studies reported no clear association, whereas others reported statistically significant associations. Notably, higher risk was linked to the specific subgroups and exposure situations. Juutilainen et al. [61] found no overall increase in adult cancer risk among people living near indoor transformer rooms but did find an increase in digestive-organ cancers among those living directly next to them. Malavolti et al. [64] similarly found no overall link between living near transformer stations and childhood leukemia, although risk was slightly higher in children aged five and older. Correa-Correa et al. [68] reported a significant link between residential exposure of 0.4 μ T or more and childhood CNS tumors, with the strongest link in children aged eleven and older. Mancini et al. [70] found that living within 50 m of overhead power lines was associated with higher acute leukemia risk in children under five, while analyses based on calculated field categories did not show a clear association. These findings suggest that children of different ages may face different types of cancer risk, though the evidence remains thin and inconsistent.

In the neurological domain, Liimatainen et al. [69] studied whether people living close to indoor transformers had a higher risk of Alzheimer's disease and found no significant association. Calderón-Garcidueñas et al. [67], on the other hand, found that weak magnetic fields can move magnetic particles naturally found in the brain, which may contribute to cellular damage and could be linked to early changes associated with neurological disease. These results indicate that biological effects can be observed under laboratory conditions even when population health data do not show a clear disease pattern.

The cardiovascular and sleep domain is supported by the similar results from two independent occupational studies. Weerasinghe et al. [66] found that factory workers exposed to magnetic fields experienced higher blood pressure and poor sleep quality, while Korenevskiy et al. [62] identified an increased risk of heart disorders in power plant workers, especially when exposure was compounded by mental and emotional stress. Although the evidence is limited to two studies and should therefore be viewed cautiously, the fact that similar findings were seen in different countries and workplaces suggests that cardiovascular health monitoring should be considered when evaluating magnetic field exposure risks.

Within the cellular and immune domain, a laboratory study by Sincak et al. [65] found that human immune cells temporarily became inflamed after exposure to ELF-MF. Importantly, yeast cells did not respond in the same manner, indicating that the observed

effect reflected a specific biological reaction in human cells rather than a general physical consequence of field exposure. Complementing this laboratory work, Korenevskiy et al. [63] found that power industry workers regularly exposed to these fields face a higher risk of immune system diseases. The converging evidence from the laboratory experiments and the worker data points to a possible connection between magnetic fields and human immune function, although the two studies differ in design and methodology, and further research would be needed to draw stronger conclusions.

Across all four domains, it can be seen that studies reporting significant results tend to find them in certain groups of people, at certain exposure levels, or for specific health outcomes, rather than across whole populations or broad disease categories. This suggests that exposure to low-frequency magnetic fields may not affect all people in the same way. Its possible health relevance may depend on who is exposed, how much exposure they receive, how long they are exposed, and which biological system is being studied. As a result, studies that do not account for these factors may be less able to detect associations that are present only in certain subgroups or exposure conditions.

To enable a more detailed, parameter-level comparison and a clearer view of which characteristics contribute to the health effects, we categorize the reviewed studies according to specific exposure characteristics. Organized by exposure setting, Table 6 outlines the studies across residential, occupational, and laboratory contexts, along with their respective exposure parameters. From this table, we subsequently regroup the studies in three complementary tables based on frequency (Table 7), intensity (Table 8), and exposure duration (Table 9).

Table 6. Reviewed studies organized by exposure setting, with exposure parameters and health findings.

Setting	Frequency	Study	Intensity	Duration	Health Effect Findings
Residential: Transformers	50 Hz	Juutilainen et al. [61]	Not directly measured/reported	Chronic residential (adult, unspecified years)	Increased risk of digestive-organ cancers
Residential: Transformers	50 Hz	Malavolti et al. [64]	0.3–1 μ T (estimated)	Chronic residential (childhood, unspecified years)	No significant association with childhood leukemia, though with a slightly higher risk at age ≥ 5
Residential: Transformers	50 Hz	Liimatainen et al. [69]	Mean 0.10–0.56 μ T (proximity-based)	Chronic residential (adult, median 3.9–4.4 years)	No significant association with Alzheimer’s risk
Residential: Power Lines	50 Hz	Mancini et al. [70]	<0.1, 0.1–<0.3, ≥ 0.3 , ≥ 0.4 μ T (modeled)	Chronic residential (childhood, unspecified years)	Increased leukemia risk in children under five within <50 m, but no association based on calculated field
Residential: Bedroom	30–800 Hz	Correa-Correa et al. [68]	<0.1 to ≥ 0.4 μ T (categorized)	Chronic residential (childhood, unspecified years)	Increased CNS tumor risk at ≥ 0.4 μ T, especially age ≥ 11
Occupational: Power Plants	50 Hz	Korenevskiy et al. [62]	Not directly measured/reported	1–9+ years, modeled	Increased occupational cardiovascular and neurological risk
Occupational: Power Plants	50 Hz	Korenevskiy et al. [63]	Not directly measured/reported	1–13+ years, modeled	Increased occupational immune-disease risk
Occupational: Factory	Not specified	Weerasinghe et al. [66]	Median 0.03–0.04 μ T (low); 0.17–0.18 μ T (high)	24 h	Increased systolic blood pressure and reduced deep sleep duration

Table 6. *Cont.*

Setting	Frequency	Study	Intensity	Duration	Health Effect Findings
Laboratory	50 Hz; 50 + 150 Hz	Sincak et al. [65]	20 μ T	Macrophages: 2 h; yeast: 24 h	Rapid reversible pro-inflammatory responses in macrophages; no significant yeast effects
Lifelong environmental + laboratory	Not specified	Calderón-Garcidueñas et al. [67]	30–50 μ T DC; 25–1000 mT AC	Autopsy tissue: unspecified time	Magnetic particles moved under weak DC fields (geomagnetic range), associated with cellular damage and early signs of neurological disease.

Table 7. Reviewed studies grouped by exposure frequency and associated health outcomes.

Frequency	Number of Studies	Study	Health Effect Findings
50 Hz	7	Juutilainen et al. [61], Korenevskiy et al. [62,63], Malavolti et al. [64], Sincak et al. [65], Liimatainen et al. [69], Mancini et al. [70]	Increased risk of digestive-organ cancers (Juutilainen); increased occupational cardiovascular and neurological risk (Korenevskiy a); increased occupational immune-disease risk (Korenevskiy b); no significant association with childhood leukemia, though with a slightly higher risk at age ≥ 5 (Malavolti); no significant association with Alzheimer's risk (Liimatainen); increased leukemia risk in children under five within <50 m, but no association based on calculated field (Mancini); rapid reversible pro-inflammatory responses in macrophages; no significant yeast effects (Sincak)
50 + 150 Hz	1	Sincak et al. [65]	Rapid reversible pro-inflammatory responses in macrophages; no significant yeast effects
30–800 Hz	1	Correa-Correa et al. [68]	Increased CNS tumor risk at ≥ 0.4 μ T, especially age ≥ 11
Not specified	2	Weerasinghe et al. [66], Calderón-Garcidueñas et al. [67]	Increased systolic blood pressure and reduced deep sleep duration (Weerasinghe); magnetic-particle movement associated with cellular damage and early signs of neurological disease (Calderón-Garcidueñas)

Table 8. Reviewed studies grouped by exposure intensity and associated health outcomes.

Intensity Range	Number of Studies	Study	Health Effect Findings
<0.1 μ T	2	Mancini et al. [70] (<0.1 μ T), Weerasinghe et al. [66] (0.03–0.04 μ T)	No significant leukemia link (Mancini); used as a low-exposure comparison group (Weerasinghe)
0.1– <0.3 μ T	3	Liimatainen et al. [69] (0.1 μ T), Mancini et al. [70] (0.1– <0.3 μ T), Weerasinghe et al. [66] (0.17–0.18 μ T)	No link to Alzheimer's risk found (Liimatainen); no significant leukemia link (Mancini); increased systolic blood pressure and reduced deep sleep duration (Weerasinghe)
≥ 0.3 μ T	5	Malavolti et al. [64] (0.3–1 μ T), Mancini et al. [70] (≥ 0.3 μ T), Correa-Correa et al. [68] (≥ 0.4 μ T), Liimatainen et al. [69] (0.56 μ T), Sincak et al. [65] (20 μ T)	No significant leukemia link; slightly higher risk in children aged ≥ 5 (Malavolti); no significant leukemia link using calculated magnetic field levels (Mancini); increased CNS tumor risk, particularly in children aged ≥ 11 (Correa-Correa); no link to Alzheimer's risk found (Liimatainen); rapid reversible pro-inflammatory responses in macrophages; no significant yeast effects (Sincak)

Table 8. *Cont.*

Intensity Range	Number of Studies	Study	Health Effect Findings
30–50 μ T DC; 25–1000 mT AC	1	Calderón-Garcidueñas et al. [67]	Magnetic-particle movement associated with cellular damage and early signs of neurological disease
Not directly measured/reported	3	Juutilainen et al. [61], Korenevskiy et al. [62,63]	Increased risk of digestive-organ cancers (Juutilainen); increased occupational cardiovascular and neurological risk (Korenevskiy a); increased occupational immune-disease risk (Korenevskiy b)

Table 9. Reviewed studies grouped by exposure duration and associated health outcomes.

Duration	Number of Studies	Study	Health Effect Findings
Chronic residential (adult, median 3.9–4.4 years)	1	Liimatainen et al. [69]	No link to Alzheimer’s risk found
Chronic residential (adult, unspecified years)	1	Juutilainen et al. [61]	Increased risk of digestive-organ cancers
Chronic residential (childhood, unspecified years)	3	Malavolti et al. [64], Mancini et al. [70], Correa-Correa et al. [68]	No significant leukemia link; slightly higher risk in children aged ≥ 5 (Malavolti); no significant leukemia link (Mancini); increased CNS tumor risk, particularly in children aged ≥ 11 (Correa-Correa)
Occupational (1–9+ years, modeled)	1	Korenevskiy et al. [62]	Increased occupational cardiovascular and neurological risk
Occupational (1–13+ years, modeled)	1	Korenevskiy et al. [63]	Increased occupational immune-disease risk
Occupational (24 h)	1	Weerasinghe et al. [66]	Increased systolic blood pressure and reduced deep sleep duration
Lab (macrophages: 2 h; yeast: 24 h)	1	Sincak et al. [65]	Rapid reversible pro-inflammatory responses in macrophages; no significant yeast effects
Lifelong environmental + lab (autopsy tissue: unspecified time)	1	Calderón-Garcidueñas et al. [67]	Magnetic-particle movement associated with cellular damage and early signs of neurological disease

A number of patterns are evident across these tables. When the studies are grouped by frequency in Table 7, most of the research centers on 50 Hz. However, the findings at this frequency are mixed, indicating that frequency alone does not explain the differences in results. Despite this, several 50 Hz studies did report concerning health impacts, such as higher cancer risks and immune system changes, showing that this frequency does have biological effects. Meanwhile, the few studies that examined other frequencies suggest that risk patterns may differ in certain contexts. For example, a study evaluating 30–800 Hz exposure in bedrooms found an increased risk of CNS tumors at higher exposure levels. Nevertheless, because so few studies examined other frequencies, we are unable to draw firm conclusions about frequency-specific risks. When grouped by exposure intensity in Table 8, negative impacts are reported more often at higher exposure levels, particularly at or above 0.3 to 0.4 μ T. For example, exposures of at least 0.4 μ T are linked to childhood CNS tumors, while 20 μ T induces a pro-inflammatory response in macrophages. However, some impacts were also observed at moderate exposure levels, including changes in blood pressure and sleep quality at approximately 0.17 to 0.18 μ T. At the same time, several other studies found no association at similar intensity levels. These mixed results suggest that intensity appears to play a role, but there is no single level where harm always happens. The findings may also depend on the exposure assessment method (measured versus modeled),

the specific health outcome examined, and the characteristics of the population being studied. Finally, looking at exposure duration (Table 9) shows that short-term exposures at work or in laboratory settings are more likely to cause temporary, reversible physiological responses, such as changes in immune responses, blood pressure, and sleep quality. In contrast, long-term residential and occupational studies generally report either no clear association or associations limited to particular subgroups, such as certain age groups or people living closest to the source. Overall, the tables suggest that exposure intensity and duration appear to be the important factors associated with health effects. Frequency appears relevant mainly due to the majority of studies reviewed examining the 50 Hz power frequency.

4. Discussion

We reviewed two complementary bodies of literature. The first focused on EV occupants' actual exposure in terms of field strength, frequency content, and spatial distribution inside the cabin. The second examined evidence on the health effects of comparable low-frequency magnetic fields. Synthesizing these findings allowed us to preliminarily assess whether the magnetic fields measured inside EVs reach levels capable of contributing to the health outcomes identified in our second review.

A key connection between the two reviews lies in the magnitude of the reported fields. The studies measuring magnetic fields in EVs show that exposure levels inside the cabin typically range from 0.01 to 5 μT under most driving conditions, with a concentrated peak of approximately 60 μT near the floor and footwell. These values can be compared with the thresholds identified in the health-effects studies. Correa-Correa et al. [68] reported a significant link between residential exposure at or above 0.4 μT and the risk of childhood CNS tumors. This level is exceeded by multiple measurements documented in the EV magnetic field studies, particularly in rear seat positions. For instance, Gryz et al. [33] reported rear seat maximum values of 1.3 to 1.5 μT , Fukui et al. [19] reported a rear seat peak of 4.67 μT during acceleration, and Szafrowski and Winiarz [58] reported 4.43 μT at the rear passenger's abdomen during acceleration. The finding that these exposure levels surpass the 0.4 μT threshold may be particularly worth further attention given how often children travel in rear seats. A similar comparison can be made with the 20 μT exposure used by Sincak et al. [65] to induce a pro-inflammatory response in human macrophages. This level is comparable to the 19.9 μT peak measured by Enegbuma and Kim [55] near the passenger floor at 80 km/h and below the 60.4 μT peak recorded by Pinto et al. [12] at the front left foot area. While these floor-level peaks are not representative of whole-body exposure, regional field effects could potentially trigger systemic responses. Consequently, the common posture of resting the feet in the footwell may expose occupants to levels near or above the threshold for detectable immune responses observed in the laboratory study.

The differences in exposure across seating positions reported in the EV studies may have health significance in the context of evidence from health-effects research. Rear seat passengers often experience field levels comparable to or higher than those in front seats. This pattern is especially relevant to findings on childhood cancer. Mancini et al. [70] found increased leukemia risk in children under five living within 50 m of overhead power lines, Correa-Correa et al. [68] reported increased CNS tumor risk in children exposed to 0.4 μT or more, and Malavolti et al. [64] found a slight increase in leukemia risk among children aged five and older living adjacent to transformer stations. Since children most often ride in the rear seats, the overlap between higher rear seat exposure and a risk threshold within the measured range underscores the need for further investigation.

Despite generally lower field levels at the head and chest compared with the floor and footwell, these locations remain relevant because they are more closely linked to

neurological and cardiovascular effects, and measurements during dynamic driving still reach levels of up to several μT in these areas. Calderón-Garcidueñas et al. [67] showed that weak magnetic fields in a laboratory can move magnetic particles inside human brain tissue and may be linked to cellular damage. They also found early signs of brain disease in all the samples examined. Although more studies are needed before we can directly compare these results to the conditions inside an EV, this discovery points to a potential pathway through which magnetic fields near the head could affect the brain.

The EV studies show that magnetic fields are stronger during acceleration and at higher speeds, a pattern that may be relevant in light of recent health-effects research. According to [66], factory workers exposed to stronger magnetic fields than the general population had increased blood pressure and worse sleep. Korenevskiy et al. [62] studied power plant workers and found an association between heart disorders and the combination of magnetic field exposure and mental stress. The EV driving environment may involve a broadly similar combination, as drivers deal with the pressure of traffic while being exposed to high field levels when the car accelerates. Should these magnetic fields have cardiovascular effects, the combined burden of driving stress and higher exposure levels in an EV should be given closer research attention.

The timing of exposure also offers another point of connection between the two reviews. Sincak et al. [65] observed that macrophages transitioned to a pro-inflammatory state within two hours of exposure and returned to their original state within 24 h. This temporary effect may appear less problematic for occasional EV users, but for professional drivers and frequent commuters, the pro-inflammatory response could be repeatedly induced before full recovery occurs between exposures. Whether this recurring pro-inflammatory response leads to cumulative or lasting harm for intensive EV users appears to be a gap in the current research.

Table 10 provides a consolidated view of the highest reported exposure levels in EV cabins across driving modes (stationary/idling, constant speed/circulation, acceleration, and braking/deceleration), load conditions, seating position (front vs. rear), and powertrain placement (FWD vs. RWD). It also summarizes health effects from our second review that have been reported at comparable field magnitudes in residential, occupational, proximity-based, or laboratory studies. The table is intended to indicate which effects could plausibly be relevant at the reported field levels, not to imply that each EV parameter has been independently examined or directly linked to every listed outcome.

Table 10. Comparative summary of highest reported magnetic field levels by driving mode, load, seating position, and powertrain placement, with associated health effects.

EV Parameter	Highest Exposure Level Reported (Study, Vehicle, Measurement Location)	Associated Health Effect
Driving mode: Stationary/Idling	4.28 μT (Fukui et al. [19], unreported, dashboard)	Increased systolic blood pressure and reduced deep sleep duration based on occupational literature (Weerasinghe); increased childhood CNS tumor risk based on residential literature (Correa-Correa); increased leukemia risk in children under five based on proximity-based residential literature (Mancini); possible associations with increased risk of digestive-organ cancers (Juutilainen), occupational cardiovascular and neurological risk (Korenevskiy a), and occupational immune-disease risk (Korenevskiy b)

Table 10. Cont.

EV Parameter	Highest Exposure Level Reported (Study, Vehicle, Measurement Location)	Associated Health Effect
Driving mode: Constant speed/Circulation	19.9 μ T (Enegbuma & Kim [55], Hyundai IONIQ, front passenger floor)	Increased systolic blood pressure and reduced deep sleep duration based on occupational literature (Weerasinghe); increased childhood CNS tumor risk based on residential literature (Correa-Correa); increased leukemia risk in children under five based on proximity-based residential literature (Mancini); possible associations with increased risk of digestive-organ cancers (Juutilainen), occupational cardiovascular and neurological risk (Korenevskiy a), and occupational immune-disease risk (Korenevskiy b)
Driving mode: Acceleration	60.4 μ T (Pinto et al. [12], unreported, driver feet)	Increased systolic blood pressure and reduced deep sleep duration based on occupational literature (Weerasinghe); increased childhood CNS tumor risk based on residential literature (Correa-Correa); increased leukemia risk in children under five based on proximity-based residential literature (Mancini); possible associations with increased risk of digestive-organ cancers (Juutilainen), occupational cardiovascular and neurological risk (Korenevskiy a), and occupational immune-disease risk (Korenevskiy b); transient macrophage pro-inflammatory response at 20 μ T
Driving mode: Braking/Deceleration	4.28 μ T (Fukui et al. [19], unreported, rear seat surface, braking)	Increased systolic blood pressure and reduced deep sleep duration based on occupational literature (Weerasinghe); increased childhood CNS tumor risk based on residential literature (Correa-Correa); increased leukemia risk in children under five based on proximity-based residential literature (Mancini); possible associations with increased risk of digestive-organ cancers (Juutilainen), occupational cardiovascular and neurological risk (Korenevskiy a), and occupational immune-disease risk (Korenevskiy b)
Load (driving current)	0.2614 μ T at 150 A simulated (Tan et al. [59], unreported, driver feet)	Increased systolic blood pressure and reduced deep sleep duration based on occupational literature (Weerasinghe); increased leukemia risk in children under five based on proximity-based residential literature (Mancini)
Starting	No MF level reported for this mode	No MF level reported for this mode
Front seat position	60.4 μ T (Pinto et al. [12], unreported, driver feet)	Increased systolic blood pressure and reduced deep sleep duration based on occupational literature (Weerasinghe); increased childhood CNS tumor risk based on residential literature (Correa-Correa); increased leukemia risk in children under five based on proximity-based residential literature (Mancini); possible associations with increased risk of digestive-organ cancers (Juutilainen), occupational cardiovascular and neurological risk (Korenevskiy a), and occupational immune-disease risk (Korenevskiy b); transient macrophage pro-inflammatory response at 20 μ T
Rear seat position	4.67 μ T (Fukui et al. [19], unreported, rear seat surface)	Increased systolic blood pressure and reduced deep sleep duration based on occupational literature (Weerasinghe); increased childhood CNS tumor risk based on residential literature (Correa-Correa); increased leukemia risk in children under five based on proximity-based residential literature (Mancini); possible associations with increased risk of digestive-organ cancers (Juutilainen), occupational cardiovascular and neurological risk (Korenevskiy a), and occupational immune-disease risk (Korenevskiy b)

Table 10. Cont.

EV Parameter	Highest Exposure Level Reported (Study, Vehicle, Measurement Location)	Associated Health Effect
Powertrain placement: FWD	19.9 μ T (Enegbuma & Kim [55], Hyundai IONIQ, front passenger floor)	Increased systolic blood pressure and reduced deep sleep duration based on occupational literature (Weerasinghe); increased childhood CNS tumor risk based on residential literature (Correa-Correa); increased leukemia risk in children under five based on proximity-based residential literature (Mancini); possible associations with increased risk of digestive-organ cancers (Juutilainen), occupational cardiovascular and neurological risk (Korenevskiy a), and occupational immune-disease risk (Korenevskiy b)
Powertrain placement: RWD	1.5 μ T (Gryz et al. [33], unreported, rear seat surface)	Increased systolic blood pressure and reduced deep sleep duration based on occupational literature (Weerasinghe); increased childhood CNS tumor risk based on residential literature (Correa-Correa); increased leukemia risk in children under five based on proximity-based residential literature (Mancini); possible associations with increased risk of digestive-organ cancers (Juutilainen), occupational cardiovascular and neurological risk (Korenevskiy a), and occupational immune-disease risk (Korenevskiy b)

5. Conclusions

This study was designed to connect what is being measured about low-frequency magnetic fields inside pure electric vehicles and what is known about the biological and health significance of such exposure. It looked at existing EMF safety guidelines, evaluated magnetic field levels recorded within pure EVs, and examined recent findings on the biological and health impacts of comparable low-frequency fields. By synthesizing evidence and analysis across these three related areas, this work provides a clearer understanding of human exposure to EMFs in EVs and identifies research priorities for future health studies aimed at developing more robust safety guidelines.

The reviewed studies on EMFs in EVs reveal generally similar patterns regardless of geographic locations, vehicle models, or testing conditions. The measured field levels inside an EV typically range from 0.01 to 5 μ T but can reach considerably higher values in specific locations. The highest field strengths are consistently observed near the floor and footwell, decreasing toward the upper body and head. These levels also fluctuate based on driving behavior and tend to increase during acceleration and at higher speeds. Rear seat measurements are often comparable to front seat measurements and can be higher in some vehicles. This is significant since children commonly sit in the rear seats. In general, EV magnetic fields vary by location, time, and driving mode, and typically remain well below the established safety limits although they may increase when the vehicle accelerates or operates under high power.

The reviewed studies on health effects report biological and health-related associations at field levels comparable to those measured inside EVs, though these findings come from occupational, residential, or laboratory settings rather than from EV occupants directly. In laboratory experiments, human immune cells temporarily entered a pro-inflammatory state following exposure to 20 μ T, a level comparable to that observed near the floor inside certain vehicles. Occupational exposure to stronger ELF-MF levels is associated with increased systolic blood pressure and reduced sleep quality. Weak magnetic fields have also been shown in laboratory experiments to move magnetic particles present in human brain tissue, which may contribute to cellular damage and could be linked to early changes associated with neurological disease. Additionally, some studies have reported increased cancer risk in children exposed to fields at or above 0.4 μ T or living near power

infrastructure, although findings across this body of literature are mixed, with other studies finding no significant association. In sum, these results indicate that EMF exposure during routine EV use can reach levels sufficient to induce biological and potentially adverse health responses reported in other populations and contexts. While direct evidence in EV occupants is currently lacking, this overlap suggests that such exposure should not be assumed to be without potential risk.

The combined evidence from both reviews highlights clear priorities for future research. Research on EMF exposure in EVs should prioritize measuring what each occupant actually receives at critical body regions such as the foot, head, and abdomen. Less targeted measurement approaches risk missing the exact exposures most relevant to human health, as magnetic field levels can vary greatly from one seat or area to another. Furthermore, children should also be kept separate in the analysis, given the rear seat exposure levels documented in the EV literature and the evidence of increased childhood cancer risk reported in the health literature. Beyond improving exposure assessment, studies measuring systolic blood pressure, sleep quality, and immune function in frequent EV users over short to medium periods would directly verify whether the cardiovascular and immune responses seen in occupational and experimental settings also occur among people who frequently use EVs. Unlike cancer, which can take many years to track, these shorter-term indicators could provide early evidence on the possible effects of regular EV use. Given that the temporary immune inflammation observed by Sincak et al. [65] could be repeatedly triggered by daily driving, future studies should involve frequent and professional EV users and should be specifically designed to analyze the cumulative consequences of repeated exposures instead of single or occasional exposures. Additionally, laboratory studies that employ exposure patterns similar to what EVs actually generate would help test whether the biological responses observed under single frequency conditions are also present in the complex electromagnetic environments of EVs. In particular, the finding by Calderón-Garcidueñas et al. [67] that weak magnetic fields can shift magnetic particles in human brain tissue should be followed up using field intensities and conditions that match those measured at head height inside EVs.

A shared observation in both reviews concerns the importance of how exposure is measured. In the health-effects studies, results can change depending on whether researchers use distance-based estimates, calculated field levels, or personal exposure measurements, as illustrated by the contrasting results in a study by Mancini et al. [70]. Future health studies, including long-term investigations of EV users, would therefore benefit from careful consideration of exposure assessment methods. In the EV magnetic field studies, researchers used different instruments, frequency ranges, measurement locations, and driving modes, which make it hard to compare studies and to estimate how much exposure different users receive. Broader adoption of the IEC 62764-1:2022 standard, along with detailed and consistent reporting of field levels by body position, frequency content, and driving condition, would greatly improve the comparability of EV exposure measurements across studies and enhance their usefulness for health risk assessment. Reporting should also include exposure duration, occupant characteristics such as age and seating position, and use patterns among groups such as daily commuters, professional drivers, and families with young children. As the health evidence suggests, who is exposed, how long exposure lasts, and how often exposure occurs may be just as important as the field strength itself. Researchers should therefore collect and report these data in their studies.

The findings from both reviews also have implications for the development and application of international EMF exposure guidelines. The existing ICNIRP and IEEE guidelines focus on preventing short-term, well-established effects such as nerve stimulation, and

their reference levels are well above the field levels typically measured inside EVs during routine driving. However, the evidence reviewed in our analysis suggests that various biological and health effects, ranging from increased childhood cancer risk to cardiovascular impacts and immune cell inflammation, can occur at levels far below these established safety thresholds. While this disparity between regulatory limits and the lower field levels at which health effects have been observed is not a new concern, the growing adoption of EVs may broaden the relevance of this concern, as an increasingly large population is now exposed to these fields on a daily basis. In addition, the existing guidelines do not fully account for the complex, dynamic electromagnetic environments unique to EVs. As the volume of EV-specific exposure and health-effects research grows, its findings should be incorporated into future updates of ICNIRP and IEEE standards to ensure that regulation reflects evolving evidence. Until more is known, it is sensible to be cautious, especially when it comes to protecting children and other vulnerable EV occupants.

Finally, we highlight two additional considerations that fall outside the scope of the present review but deserve attention in future work. First, our synthesis was limited to peer-reviewed academic literature and did not include the technical assessments of EMF exposure in EVs produced by government-commissioned research programs. These assessments may offer valuable insights not captured in the academic literature and could be incorporated into future, more comprehensive evaluations of EV exposure. Second, our review did not investigate manufacturer-level efforts to reduce cabin magnetic field exposure, such as shielding designs or component placement optimization. The exposure levels identified in this review show the need to understand current industry practices and whether they help reduce occupant exposure. This work would support the health research priorities discussed above and may help inform future updates to EV safety guidelines.

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Appendix A. Global Landscape of EMF Exposure Limits

Most countries or regions base their EMF exposure limits on the guidelines set by the ICNIRP or the IEEE. Research shows that many countries adopt exposure limits that follow ICNIRP or use similar levels [27,71]. A smaller number of areas, mainly the United States and its territories, use limits derived from the IEEE standards [72].

A significant number of countries that follow ICNIRP limits are part of the European Union (EU; [73]). The EU, through Council Recommendation 1999/519/EC, recommended that member states follow the ICNIRP exposure limits to protect people from EMF [74,75]. Countries within the EU handle this recommendation in different ways [76,77]. Some nations have incorporated the EU Council Recommendation into their national regulations, such as Estonia, Greece, Austria, Portugal, Romania, Slovakia, Czech Republic, Hungary, Spain, and Cyprus, while others, including Germany, Belgium, and Luxembourg, adopt these standards along with additional precautionary measures for sensitive areas such as schools and hospitals [76,78]. Finland, France, Croatia, and Luxembourg also follow the EU reference values but add extra requirements. A number of countries have not directly adopted the EU Council Recommendation. Nations such as Bulgaria, Ireland, Sweden, Latvia, and Malta either lack specific legal regulations or depend on non-binding guidance. In contrast, a group of nations, including Italy, Lithuania, Poland, Slovenia, Denmark, and the Netherlands, enforces regulations that are stricter than the ICNIRP recommendation. These countries often set lower exposure limits, especially for sensitive locations such as schools and hospitals.

While many EU countries follow the 1999 Council Recommendation and ICNIRP guidelines, non-EU European countries approach EMF safety in a variety of ways [78]. Some countries have minimal rules, while others enforce more restrictive limits than what the EU requires. For instance, Great Britain, Iceland, and Monaco do not have specific legal regulations for exposure limits but instead rely on non-mandatory guidance. In contrast, Switzerland and Liechtenstein set strict limits, separating old and new infrastructure and limiting magnetic fields to just 1 μT for new installations [78]. Similarly, Serbia enforces limits for electric and magnetic fields below those of the EU Recommendation. Other nations such as Norway and San Marino combine international reference values with extra precautionary limits.

Outside Europe, most countries that regulate EMF exposure use ICNIRP guidelines as a reference, but the ways they apply and enforce these standards vary significantly. In the Asia-Pacific region, Japan applies ICNIRP-based limits [79], while Republic of Korea uses both ICNIRP and IEEE references depending on applications [80,81]. Singapore, Malaysia, Thailand, Taiwan, and the Philippines all reference ICNIRP in their regulations, typically through telecommunications or environmental protection authorities [82–86]. In Australia and New Zealand, their respective radiation protection agencies similarly base their EMF standards on ICNIRP guidelines [87,88]. Across the Middle East, countries such as Saudi Arabia, the United Arab Emirates, and Turkey reference ICNIRP limits in both telecommunications and environmental regulations [89–91]. Many African nations, including South Africa, Tanzania, and Nigeria, also align with ICNIRP [92–94], as do most Latin American countries, where safety rules in Argentina, Brazil, and Peru adopt ICNIRP-based limits within their regulatory systems [95–97].

A few countries, however, have chosen to set their own standards instead of directly adopting international guidelines, or refer to those guidelines without fully adopting them. Russia maintains strict exposure limits based on decades of independent research, with levels often many times lower than ICNIRP's recommendations [98–100]. China's standards draw from the ICNIRP and IEEE guidelines but are adjusted to fit local environmental protection practices [101]. As a result, they have more restrictive limits at some frequencies [26,27]. India initially based its regulations on ICNIRP's recommendations but later set more cautious limits for base station emissions, making them ten times stricter than ICNIRP's, and for mobile devices, it follows the U.S. Federal Communications Commission (FCC) limits [81,102,103]. In Canada, a nationally developed guideline is used for

radiofrequency exposure, although its limits are mostly in line with ICNIRP and IEEE recommendations [81,104,105].

In the United States, the federal government handles electromagnetic safety differently depending on the type of field involved. For radiofrequency fields between 300 kHz and 100 GHz, the FCC applies limits adopted in 1996 that follow recommendations from the IEEE and the National Council on Radiation Protection and Measurements (NCRP) [106]. In contrast, there are no federal safety limits for the power-frequency and other low- and intermediate-frequency fields most relevant to EV powertrains [107,108]. While a handful of states such as Florida, Minnesota, New York, New Jersey, and Oregon have set their own limits for EMFs from power lines, these state-level standards vary widely in their specific requirements [27,109,110]. Consequently, researchers working in this area typically compare their measurement results against various international guidelines to assess safety.

Table A1 summarizes the low-frequency magnetic field limits for the general public at power line frequencies (50–60 Hz) in the countries and regions discussed in this section. Most countries with binding limits follow the ICNIRP 2010 level of 200 μ T. Some countries, such as Italy, Poland, Lithuania, Slovenia, Denmark, the Netherlands, Switzerland, Liechtenstein, Serbia, and Russia, apply stricter limits than the ICNIRP standard, while others, such as Bulgaria, Ireland, Sweden, Latvia, Malta, Great Britain, Iceland, and Monaco, have no binding limit and rely on non-mandatory guidance. Uniquely, Republic of Korea references both ICNIRP and IEEE depending on the application. Under IEEE C95.1-2019, the unrestricted-environment reference levels are 904 μ T for the head and torso and about 63.2 mT for the limbs at 60 Hz. Both values are significantly higher than the ICNIRP reference level. Unlike many other countries, the United States does not set a federal limit for low-frequency fields. The FCC only regulates radiofrequency fields, which range from 300 kHz to 100 GHz. This means that the low- and intermediate-frequency fields most relevant to EV powertrains remain unregulated at the federal level. We should note that the limits shown apply to the general public. Countries with stricter or locally adapted standards are not fully represented, because the specific numbers for these were not clearly or consistently reported across the sources we reviewed.

Table A1. General public low-frequency B-field limits at power frequency (50–60 Hz) across discussed jurisdictions.

Country/Region	Framework Basis	Low-Frequency B-Field Limit (50–60 Hz, General Public)
Estonia, Greece, Austria, Portugal, Romania, Slovakia, Czech Republic, Hungary, Spain, Cyprus	ICNIRP/EU Recommendation	200 μ T
Germany, Belgium, Luxembourg, Finland, France, Croatia, Norway, San Marino	ICNIRP/EU Recommendation	200 μ T; additional precautionary limits apply
Bulgaria, Ireland, Sweden, Latvia, Malta, Great Britain, Iceland, Monaco	Non-binding guidance	No specific binding limit
Italy, Poland, Lithuania, Slovenia, Denmark, Netherlands	Stricter than ICNIRP/EU Recommendation	Below 200 μ T; specific limits apply by location type
Switzerland, Liechtenstein	Stricter than ICNIRP/EU Recommendation	1 μ T for new installations
Serbia	Stricter than ICNIRP/EU Recommendation	Below 200 μ T
Japan, Singapore, Malaysia, Thailand, Taiwan, Philippines	ICNIRP-based	200 μ T

Table A1. Cont.

Country/Region	Framework Basis	Low-Frequency B-Field Limit (50–60 Hz, General Public)
Republic of Korea	ICNIRP and IEEE	200 μ T (ICNIRP), or 904 μ T for the head and torso and 63.2 mT for the limbs at 60 Hz (IEEE), depending on applications.
Australia, New Zealand	ICNIRP-based	200 μ T
Saudi Arabia, United Arab Emirates, Turkey	ICNIRP-based	200 μ T
South Africa, Tanzania, Nigeria	ICNIRP-based	200 μ T
Argentina, Brazil, Peru	ICNIRP-based	200 μ T
India	ICNIRP-based	200 μ T; stricter limits for base station emissions
China	National standards drawing from ICNIRP and IEEE	Locally adapted; more restrictive than 200 μ T at some frequencies
Russia	Independent national standards	Below 200 μ T
Canada	National RF guideline (aligned broadly with ICNIRP/IEEE)	200 μ T (non-mandatory advisory recommendations)
United States	IEEE/FCC (RF only)	No federal low-frequency limit

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