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Passenger Exposure to Magnetic Fields in Electric Vehicles

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Additional information is available at the end of the chapter

Abstract

In electric vehicles, passengers sit very close to an electric system of significant power, usually for a considerable amount of time. The relatively high currents achieved in these systems and the short distances between the power devices and the passengers mean that the latter could be exposed to relevant magnetic fields. This implies that it becomes necessary to evaluate the electromagnetic environment in the interior of these vehicles before releasing them in the market. Moreover, the hazards of magnetic field exposure must be taken into account when designing electric vehicles and their components. For this purpose, estimation tools based on finite element simulations can prove to be very useful. With appropriate design guidelines, it might be possible to make electric vehicles safe from the electromagnetic radiation point of view.

Keywords: electric vehicles, electromagnetic radiation, magnetic field exposure, occupational safety

1. Introduction

The traction drive of an electric car is an electrical system of considerable power, ranging from 40 to 120 kW. Even higher power levels are found in high-end models or in other vehicles such as electric buses. These power levels are usually achieved with high currents rather than voltages. Specifically, most commercial vehicles nowadays work with voltage levels below 400 V, which implies currents of the order of hundreds of amperes. This means that these traction drives could generate magnetic fields of considerable strength when compared to other conventional sources.

At the same time, distances between these magnetic field generators and the passengers are relatively short in most vehicles; for instance, it is usual to place the battery pack as far as possible from the bodywork to minimize the risk of battery damage and its consequences in case of crash; this implies positioning them just under or behind the passenger seats [1]. Consequently, there could be hundreds of amperes circulating some centimeters away from the passengers during strong accelerations or deep regenerative braking.

The combination of high currents and short distances involves some risks due to the presence of strong magnetic fields. These fields can potentially have undesired effects on electric and electronics devices, but also on living beings inside the vehicle, or close to it. The first effects are known as electromagnetic interference (EMI) and are analyzed within the discipline of electromagnetic compatibility (EMC), whose main goal is to ensure proper operation of operational equipment in a common electromagnetic environment. This is usually done by limiting or conditioning the electromagnetic fields (EMFs) emitted by each device, but mostly by immunizing them so that they are not affected by EMI coming from the rest of the devices.

The second effects are named electromagnetic radiation (EMR) and belong to the field known as bioelectromagnetism or bioelectromagnetics, which studies all kinds of interactions between EMFs and biological systems. EMR is usually classified into ionizing and nonionizing radiation, depending on its capability to ionize atoms and therefore to break chemical bonds. This is only possible if the radiation carries a high amount of energy, and hence ionizing capability is directly associated with wavelength and thus with frequency. The boundary between nonionizing and ionizing EMR is located in the ultraviolet range of the electromagnetic spectrum. In this sense, all the radiation emitted by an electric vehicle is nonionizing.

The relationship between nonionizing EMR and human health has been studied for decades. In 1996, the World Health Organization (WHO) established the *International EMF Project* to assess the scientific evidence of possible health effects of low-frequency EMR (from 0 to 300 GHz), encouraging focused research to fill important gaps in knowledge and the development of internationally acceptable standards limiting EMF exposure [2]. At present, some possible consequences of low-frequency EMF exposure are still Unclear. Namely health effects caused by long-term exposure (such as cancer or neurodegenerative disorders) are mentioned in the literature, although conclusive results have not been obtained. Many long-term studies have been described as questionable and of low repeatability. Moreover, it could be argued that long-term effects are impossible to determine with certainty, since they take years or even decades to appear. Hence, long-term consequences are a source of discussion within the scientific community.

On the other hand, short-term nonionizing effects are well established, and their mechanisms are well known. These biological effects occur as soon as the exposure begins, and they disappear when it ceases, or shortly after. They are caused by extremely strong low-frequency (up to a few hundred kHz) and strong medium-frequency EMFs (radio waves and microwaves up to 300 GHz), and thus they are also known as acute effects. They may be classified into two main groups: electrostimulant effects and thermal effects. The former are a consequence of the coupling between low-frequency fields and living matter, an example of this would be induced currents in some organic tissues generated by an external magnetic field. The latter are due to

energy exchange between medium-frequency fields and biological tissues, which produces a temperature increase in those body parts affected. Thermal effects are usually negligible for field frequencies below 100 kHz, but become increasingly significant as frequency grows. Current standards, guidelines, and recommendations regarding maximum exposure values are developed considering these acute effects.

This chapter is intended to introduce the reader to the topic of magnetic field exposure in electric vehicles (EVs). For further information, a considerable number of references are provided at the end. The chapter is divided into different sections as follows:

- Section 2, Problem description, describes the main sources of magnetic field within an EV and the corresponding properties of those fields.

- Section 3, Prevention guidelines and standards, presents the two most accepted criteria for limiting magnetic field exposure.

- Section 4, State of the art, summarizes the most relevant studies published to date about magnetic field exposure in electric vehicles, as well as their main conclusions.

- Section 5, Design guidelines, lists some design modifications and considerations that can help improve the safety on an EV from the EMR point of view.

- Section 6, Discussion, presents some arguable ideas about magnetic field exposure in EVs.

2. Problem description

Electric vehicles are one of the most relevant applications in which power devices and general public share a common space. Other well-known precedents are power lines close to houses or buildings, electric trains and trams, and household appliances, to cite a few examples. However, the specific characteristics of EVs could make this issue particularly worrying from the point of view of magnetic field exposure. The combination of high current levels, short average distances between equipment and passengers, and long exposure duration is especially detrimental in this application.

As mentioned in the "Introduction" section, power levels in electric vehicles are of the order of tens of kW, while voltage levels rarely exceed 600 V, as shown in **Table 1**. This implies that current levels usually reach hundreds of amperes. There are not many applications in which people are close to wires or devices carrying such high currents. Besides, the present trend in EVs nowadays consists in reducing voltage levels as much as possible, which implies even higher currents. Paradoxically, lower voltages imply improved safety in case of short circuit or electrocution, but also reduced safety from the point of view of magnetic field exposure.

Second, distances between the traction drive and the passengers are usually short. For a typical electric car, values range from 0.2 to 3.0 m depending on the location of all the power devices and power cables. In this sense, the topology and the configuration of the vehicle (i.e., how the power devices are located within the available space) are particularly relevant:

- For instance, there are some differences between those vehicles that add a DC-DC converter connecting the batteries and the inverter as those who do not (see **Figure 1**). Without such DC-DC, the battery must have enough voltage for the inverter to drive the electrical machine in every required operating point (torque-speed). This is usually done reaching a compromise between battery voltage, which should not be too high (using too many cells in series increase balancing and safety requirements) and machine voltage, which should not be too low (lower voltages imply higher currents and lower number of turns in the windings). In general, adding a DC-DC allows for higher voltages in the drive, which improves magnetic field exposure but could worsen electric field exposure. However, in most cases the DC-DC aims to reduce battery voltage, and thus battery current increases. Hence, if the batteries are placed close to the passengers, they could suffer from higher magnetic fields.

- There are also some differences between pure electric vehicles and hybrid electric vehicles. The former have simpler traction systems, with fewer devices and mechanisms, which can be easily accommodated within the available space. On the other hand, the power train of the latter comprises more equipment, and thus they are more prone to suffer from room issues. Having more flexibility to distribute the power devices within the vehicle is always a good thing, and magnetic field exposure is another aspect that benefits from it, since certain parts can be moved away from the passengers. Nevertheless, pure electric vehicles use more electric power than their counterparts. Considering that voltage levels are similar (see **Table 1**), this means that pure EVs use higher currents and thus they generate stronger magnetic fields. In general, it could be expected that the second factor (stronger fields) weighs more than the first one (longer distances), so that pure EVs should imply higher exposure levels than hybrid vehicles.

- Finally, the type of drive also has some influence over passenger field exposure, namely those vehicles with rear-wheel drives usually place most of the traction equipment (i.e., the electrical machine and the inverter) in the rear part of the vehicle, while front-wheel vehicles place it in the front part. As cars are given aerodynamic shapes to minimize aerodynamic drag, the front part is usually longer than the rear part, and distances between the front wheels and the front seats are usually longer than those between the rear wheels and the rear seats, as shown by the two examples in **Figure 2**. This means that vehicles with front-wheel drives will usually have longer distances between these power devices and the closest passengers.

Third, regarding the duration of the exposure, it is important to note that general public is subject to electromagnetic fields generated by EVs for a considerable amount of time, significantly longer than other daily exposures such as household appliances. From the results presented in [5, 6], it can be concluded that European citizens spend an average of 1 h and 25 min per working day driving their cars. Even if an appreciable part of that time is spent with the vehicle stopped (e.g., traffic lights or traffic jams), situation in which magnetic fields should be minimum, the duration of the exposure is still rather long. In the United States of America, these average times are probably even longer, up to 2 hours in average. It is important to note here that, in the case of low-frequency magnetic fields and health effects, it is not

necessary to take exposure duration into account at the moment, since there is no scientific proof of any health consequences due to this type of exposure.

Model	Type	Drive	Power level	Voltage level
Mitsubishi i-MiEV				
Peugeot iOn	BEV	Rear wheel	49 kW	400 V_{DC}
Citroën C-Zero				
Nissan LEAF	BEV	Front wheel	80 kW	400 V_{DC}
BMW i3	BEV	Rear wheel	125 kW	500 V_{DC}
Tesla model S	BEV	Rear wheel	235 kW	650 V_{DC}
Toyota Prius (3rd gen.)	HV	Front wheel	74 kW	400 V_{DC}
Toyota Prius PHV	PHV	Front wheel	60 kW	350 V_{DC}
Chevrolet Volt	PHV	Front wheel	55 kW (x2)	400 V_{DC}

BEV = battery electric vehicle; HV = hybrid vehicle; PHV = plug-in hybrid vehicle.

Table 1. Power and voltage levels of some commercial models of hybrid and electric vehicles.
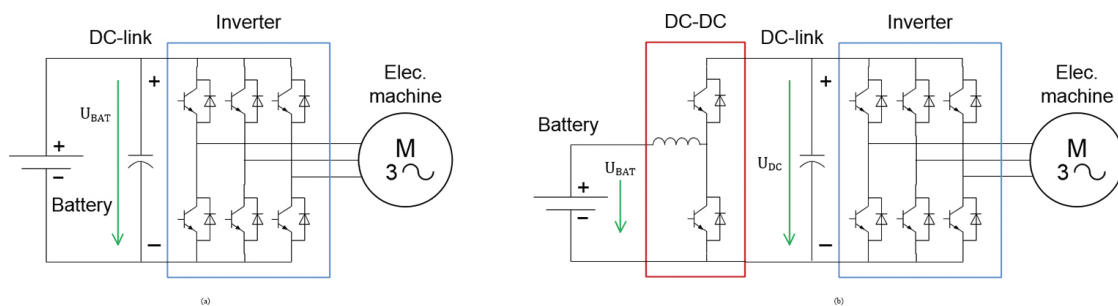

Figure 1. (a) Most common topology in electric cars nowadays. (b) Alternative topology, in which a DC-DC converter is added between the batteries and the inverter.
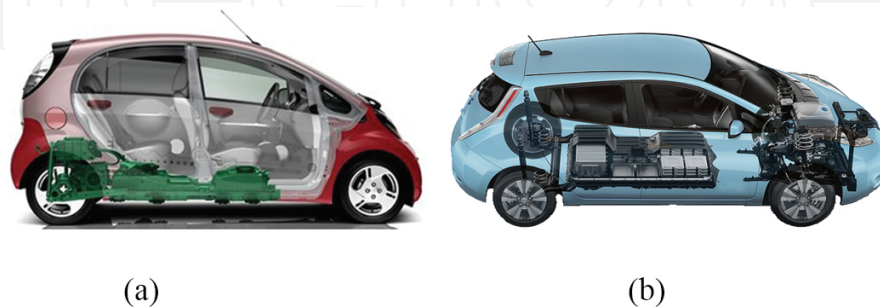

(a)   (b)

Figure 2. Schematics of two well-known pure EVs, showing the position of the main power devices: batteries, inverter, and electrical machine. (a) Rear-wheel drive and (b) front-wheel drive. Original images extracted from [3, 4] and modified by the authors.

In summary, magnetic fields in EVs could become an issue from the point of view of human health due to a combination of three factors: average and peak current levels, short distances between field generators and the passengers, and lengthy exposures.

2.1. Characteristics of the magnetic field generated by an EV

Under static electromagnetic conditions, electric fields basically depend on the voltage levels and on the distances between the passenger and the corresponding power equipment (Coulomb's law). Similarly, magnetic fields depend on the current levels and on that same distances (Biot-Savart law). In other words, when these physical magnitudes do not change over time, both fields are not coupled and they can be studied separately.

However, most electrical systems, EVs included, are characterized by time-varying electric magnitudes. In the most general case, and according to Maxwell's equations, both fields are coupled and their dependence with respect to variables such as voltages and currents is much more complex than those given by Coulomb and Biot-Savart laws. Fortunately, it is not necessary to work with Maxwell's equations in many cases, in which quasistatic approximations are applicable. Specifically, when the frequencies of the electromagnetic phenomena are low—so that propagation speed can be considered infinite [7]—a quasistatic model can be used, which provides an intermediate solution between the most general dynamic case (Maxwell's equations) and the purely static case (Coulomb and Biot-Savart laws). In this sense, a quasistatic system evolves from one state to another as if it was a static system [8].

Depending on the particular quasistatic model employed (each variant represents a different approximation of Maxwell's equations), the simplifications adopted will vary. In this particular case, Darwin's model is used, which considers both capacitive and inductive effects and which incorporates magnetic field contribution to total electric field (Faraday's law) [8]. In Darwin's model, Biot-Savart law is directly applicable, the only difference being that currents and magnetic fields are time-varying variables. However, Coulomb's law must be extended to account for magnetic induction. In other words, magnetic fields still depend on currents and distances, but also on time, while electric fields depend on voltages, distances, time, and on magnetic fields.

Electric vehicles constitute an application in which quasistatic models are appropriate, since frequencies are generally low. There are basically two types of frequencies in an electrical drive, such as those propelling EVs:

1. Fundamental frequencies: These are the lowest frequencies in the system, and they are related to the operating point of the drive. For example, in a steady-state situation, fundamental frequency would be roughly 0 Hz (DC) for the battery current and 100 Hz for a 2000-rpm 50 Hz synchronous machine working at 4000 rpm in the flux-weakening region. During transients, some of these fundamental frequencies will show harmonic content. One example of this is power peaks in the batteries, which involve low-frequency harmonics in battery current. In general, fundamental frequencies will be very low, of the order of hundreds of Hertz at most. However, the absence of steady state in some situations, such as urban driving, implies a wide-frequency spectrum.

2. Switching frequencies: These frequency values and their corresponding harmonic components are given by the operation of power semiconductors such as insulated-gate bipolar transistors (IGBTs) and diodes. They are defined by many factors, starting with the modulation technique (hysteresis band, pulse width modulation (PWM), space vector modulation (SVM), direct torque control (DTC), etc.), and also on the inductance value of the corresponding filters. For those which use variable-switching frequency, its values will depend on the operating point as well.

More importantly, switching frequencies change significantly with power electronics technology. For instance, there is a huge difference between conventional IGBTs, fast IGBTs, and silicon carbide (SiC) metal-oxide-semiconductor field-effect transistors (MOSFETs). The former usually work at frequencies ranging from 2 to 20 kHz. Fast IGBTs can reach up to 50 kHz in many applications, while SiC MOSFETs are already exceeding frequencies over 150 kHz. Given the voltage levels usually employed in commercial EVs, there is no way to exclude any of the above three major technologies, so all of them are eligible for this application.

In summary, magnetic field frequencies can change considerably from one vehicle to another. According to current EV designs, and considering the technologies implemented in them (conventional IGBTs, and synchronous or asynchronous machines), it seems reasonable to expect fundamental and switching frequencies up to 10 kHz, with relevant harmonic components up to 300 kHz. These values are classified as "low and extremely low frequencies" from the point of view of electromagnetic exposure. Be that as it may, electromagnetic fields generated by EVs present a relatively wide-frequency spectrum, from 0 Hz to hundreds of kHz.

2.2. Other considerations

There are many magnetic field generators in a vehicle, besides the traction drive itself. Examples present not only in EVs but also in conventional ICE-based vehicles are other power equipment such as the air-conditioning system, but also magnetized steel-belted tires, which are one of the main sources of extremely low-frequency magnetic fields in conventional vehicles. This unintentional magnetization is a consequence of the manufacturing process, and the result is a magnetic field whose frequency depends on the vehicle speed, ranging from 0 to 20 Hz [9, 10]. This field is of considerable strength but attenuates very quickly as distance increases. Hence, maximum exposure values usually take place in the area of the feet [11, 12]. According to some authors, this source of magnetic field is negligible when considering magnetic field exposure inside hybrid and electric cars [13], but this point is not completely clear.

Nonetheless, all magnetic field generators contribute to overall magnetic field exposure, and therefore should be included in EMR studies. It is important to state here that magnetic field exposure must be assessed globally (total magnetic field), and not individually (magnetic field generated by each device or piece of equipment). See Section 3.1 for further information and corresponding references about exposure assessment.

There are other factors that may influence magnetic field exposure in a positive way. For instance, the results presented in Ref. [14] suggest that the car body shell could behave as a minor magnetic shield for some frequencies. Therefore, constructive aspects such as the shape, material, and thickness of the body shell could affect magnetic exposure.

It is also convenient to consider which operating points are potentially more hazardous for human health. Under normal operation of the vehicle, power/current peaks will be higher during strong accelerations than during deep regenerative braking. This is due to two main reasons: the passive nature of some of the movement resistances (rolling resistance and aerodynamic drag), which implies that both of them will always oppose movement, and the global energy efficiency of the traction drive. Notice that driving style will heavily impact total magnetic exposure in EVs: the more aggressive the driving style the higher the magnetic fields within the vehicle.

Nevertheless, there is another situation which could involve potentially hazardous exposure for passengers, or even for pedestrians that are close to the vehicle: fast charging. As battery technology improves, higher recharge rates are achieved, which obviously imply higher currents, and hence stronger magnetic fields. Nowadays, charge rates of 2–4 C are already usual, with even higher values reachable in the near future [15, 16]. Therefore, magnetic field generation must be studied not only during normal operation of the vehicle but also during fast charging. As a general rule, it is highly advisable to remain outside of the vehicle, and at some distance from it, while fast charge is in process.

Finally, it is important to consider the wide variety of electric vehicles that exit nowadays, and how their different configurations, topologies, and power levels affect magnetic field exposure. Some considerations have already been mentioned in this chapter about vehicle configuration (front-wheel vs. rear-wheel traction, for instance; another example would be battery place-ment), and also about the power topology (significant differences arise when adding a DC-DC converter, or when using hybrid energy storage systems that combine batteries and superca-pacitors for increased performance [17]). The largest differences, however, appear when considering electric vehicles of different types, such as motorbikes, buses, racing cars, or even electric planes [18, 19]. Magnetic exposure in these other vehicles could be very different when compared to electric cars, depending on the power levels involved and on the distances between the power equipment and the closest passengers.

3. Prevention guidelines and standards

Magnetic field exposure assessment is a two-step process: first, one must characterize the magnetic field inside the vehicle (either by estimation or by measurement). The second step involves determining whether the obtained values could be hazardous for the passengers. Both tasks can prove very challenging, and thus any guidance is welcome. In this sense, there are some standards and guidelines that help with the second step. This section is dedicated to these documents.

Concern regarding potentially hazardous consequences of nonionizing EMR started to raise some decades ago, around the 1950s and 1960s, first about radio waves and microwaves, and more recently about low-intensity fields as well, such as those generated by power lines, cell phones, and Wi-Fi devices. The effects of nonionizing electromagnetic fields on the human body have been studied for many years already, and the results are conclusive in some cases and inconclusive in others [20–23].

Basically, there are two types of effects that electromagnetic fields can have on biological tissues: short-term and long-term effects. Short-term effects, also known as acute effects, are those that appear instantaneously, or minutes after the beginning of the exposure. In general, these effects only take place under fields of considerable intensity, and disappear as exposure ceases. The biological mechanisms involved in these short-term effects are relatively well known, as well as the field values (intensity and frequency) that cause them [24–27]. They are usually classified into two main groups: electrostimulant effects and thermal effects. The former are caused by the interaction between low-frequency fields and living matter, either by polarization and dipole reorientation produced by electric fields, or due to induced currents generated by magnetic fields (for instance, a strong alternate magnetic field can induce electrical currents capable of stimulating nerves and muscles in an undesired way). The latter refer to the exchange of energy between fields and tissues, which rises their temperature. These thermal effects are completely negligible for frequencies under 100 kHz, but become relevant at higher frequencies (consider, for the sake of illustration, the operating principle of a microwave oven, whose working frequency is around 2.45 GHz). Electrostimulant effects are instantaneous, while thermal effects have a time constant of minutes.

Long-term effects, on the other hand, are those that could appear after months or years of exposure. Several studies have tried to determine the relationship between long-term exposure to electromagnetic fields and different pathologies (cancer, neurodegenerative disorders, etc.), without finding conclusive evidence for it. Approximately half of these studies show small correlations, just statistically significant, between long-term exposure and these illnesses [28]. In any case, the possibility of such relationships made the International Agency for Research on Cancer (IARC) to classify low-intensity, low-frequency electromagnetic fields, and also radiofrequency electromagnetic fields, as "possibly carcinogenic to humans (Group 2B)" [24, 25].

Generally speaking, it is extremely difficult to establish direct biological effects caused by long-term exposure, and to obtain reproducible results [23]. As a consequence, standards and guidelines to limit human exposure are elaborated based only on well-known, scientifically proven, short-term effects (with appropriate safety factors), and therefore long-term effects are not taken into account. This applies to the two most extended guidelines nowadays, those from the International Commission on Non-Ionizing Radiation Protection (ICNIRP) and those from the Institute of Electrical and Electronic Engineers (IEEE). Both are briefly described subsequently.

3.1. ICNIRP's guidelines

The most extended criteria for recommended exposure limit to EMFs were first proposed by the International Commission on Non-Ionizing Radiation Protection (ICNIRP) in 1998 [22]. These guidelines are based on current scientific evidence, as well as risk analysis performed by the World Health Organization (WHO). They establish protection recommendations considering well-known mechanisms and appropriate security factors, the latter being due mostly to scientific uncertainty.

Eleven years after their first publication, no new scientific evidence of any adverse effects had been found [29], a reason why a review of the guidelines on limitation to exposure to high-frequency EMFs (100 kHz to 300 GHz) was considered unnecessary. Nevertheless, concerning static EMFs and extremely low-frequency EMFs (1 Hz to 100 kHz), special guidelines were published in 2009 [30] and 2010 [31], respectively, in an attempt to include the results of the main scientific publications during those 11 years. The referred publications not only established recommended exposure limits to EMFs but also include explanations concerning the ways these fields could affect human health. These two guidelines suggest recommended exposure limits (which are defined in terms of in-body quantities such as electrical fields and induced currents in a given tissue, which complicates exposure assessment), but they also provide reference levels for the electromagnetic environment (external electrical and magnetic field values). These levels are extremely helpful to assess magnetic field exposure, since the following consideration is usually applied: if the exposure environment complies with the field reference levels, then it can be assumed that the exposure limits are not infringed. Certainly, exceeding these reference levels does not necessarily imply that the corresponding exposure limits have been breached. In such cases, further analysis is required.

Frequency (Hz)	Magnetic field H (Am^{-1})	Magnetic flux density B (T)
1–8 Hz	$3.2 \times 10^4/f^2$	$4 \times 10^{-2}/f^2$
8–25 Hz	$4 \times 10^3 / f$	$5 \times 10^{-3}/f$
25–400 Hz	1.6×10^2	2×10^{-4}
400–3 kHz	$6.4 \times 10^4/f$	$8 \times 10^{-2}/f$
3 kHz to 10 MHz	21	2.7×10^{-5}

Notes: H and B in unperturbed RMS values. In addition, reference levels relating to tissue-heating effects need to be considered for frequencies above 100 kHz.

Table 2. ICNIRP's reference levels for general public exposure to time-varying magnetic fields.

Regarding exposure limits to EMFs, different considerations arise depending on the person affected. Thus, there is an "occupational exposure," which is applied to those individuals who are exposed to EMFs as a result of performing their regular job activities. There is also a "general public exposure," which refers to the rest of the population. In summary, ICNIRP's reference levels for static magnetic fields are 400 mT for general public (EVs passengers

included) and 2 T for occupational public [30], whereas the Earth's magnetic field ranges from 30 to 60 µT, depending on the region on the Earth. Concerning time-variant fields, the exposure limits to EMFs for "general public" are given in **Table 2** and also in **Figure 3** [31]. Notice that these values correspond to a sinusoidal, single-frequency, homogeneous magnetic field exposure.
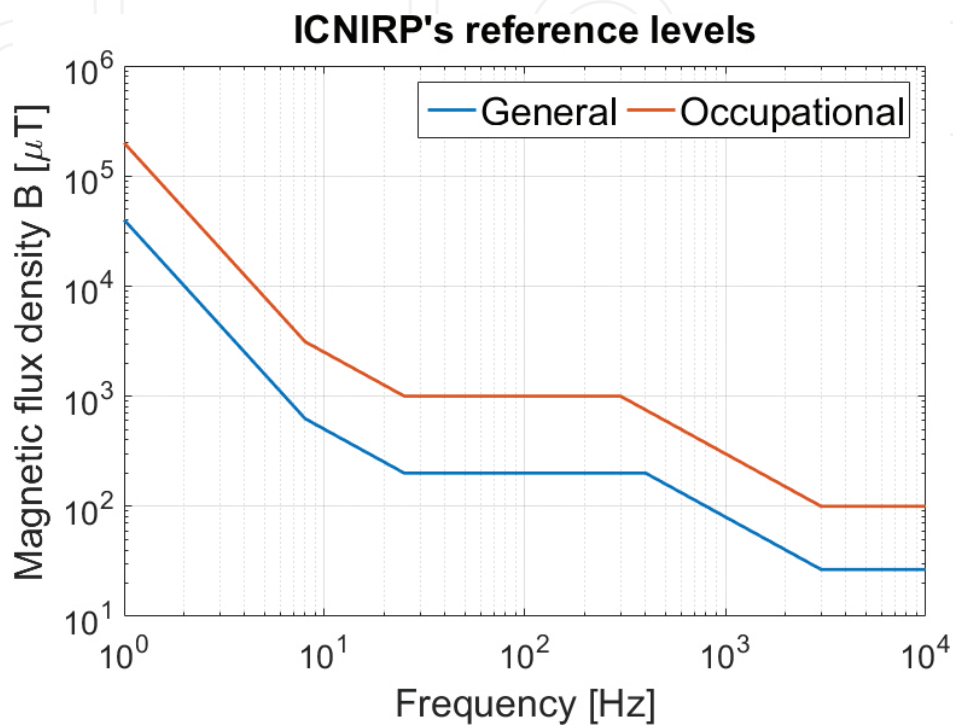

Figure 3. ICNIRP's reference levels for sinusoidal magnetic field exposure as a function of frequency (up to 10 kHz).

Notice that the above reference levels are not given as a function of time (exposure duration). They are maximum or absolute values that must never be breached. This is consistent with the fact that their corresponding exposure limits have been established based on short-term effects only. In other words, the above reference levels should guarantee the absence of harmful biological effects in the short term, based on current scientific evidence and in accordance to the experts' consensus-based criteria.

Regarding multiple frequency sinusoidal exposure, ICNIRP states that all contributions should be considered cumulative, so that the following global limit should be met:

$$\sum_{j=1\ \mathrm{Hz}}^{10\ \mathrm{MHz}} \frac{B_j}{B_{\mathrm{max},j}} \leq 1 \tag{1}$$

where B_j is the field magnitude at each given frequency, and $B_{\mathrm{max},j}$ is the reference level corresponding to that frequency. The expression for the magnetic field H is analogous.

In the case of nonsinusoidal exposure, the evaluation procedure consists in performing a frequency analysis to obtain the corresponding harmonic decomposition. After this, all harmonic components must be considered at the same time by means of Eq. (1). This methodology is simple, but very conservative, given that it assumes that all harmonic components are in phase (worst-case scenario), which is hardly real. This assumption is so pessimistic that even background noise can result in a breach of ICNIPR's reference levels if enough harmonic components are included in the calculation [32]. Consequently, a second method is recommended instead for those cases in which the number of harmonic component is considerable [31]. This alternative method consists in weighting the field components with a filter function (inverse Fourier transform) related to the reference levels [33]:

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

where EL_i is the reference level corresponding to the ith harmonic, whose frequency is f_i, while B_i and θ_i are the field amplitude and phase corresponding to that frequency, respectively, φ_i is the filter phase (also for that frequency), and t is the time. An example of implementation of the above method can be found in [9] and also in [34], in which Eq. (1) yields 99% with respect to ICNIRP's reference levels, while Eq. (2) decreases this result to 19%.

As aforementioned, ICNIRP's values are given for homogeneous exposure with respect to the whole extension of the human body. However, this assumption is not valid when magnetic field sources are close to the people affected, as might occur in an EV. Again, considering a heterogeneous exposure as homogeneous (taking maximum values as average values) results in a conservative approach. Other methods involve spatial averaging [35] or dosimetric analysis [31].

It is also important to clarify that these guidelines are not legally mandatory, and that become legally binding only if a country incorporates them into its own legislation [36]. At present, many countries and organizations have adopted these security limits. For example, the European Commission uses ICNIRP's guidelines to write regulations about EMR emission limits, applicable within the European Union [37]. Most member countries have therefore adopted these regulations, and some of them have even applied more restrictive criteria or have developed measures to legally enforce them.

3.2. IEEE's exposure standard

This subsection briefly describes the standard IEEE C95.6 [38]. This standard defines exposure levels to protect against adverse effects in humans from exposure to electric and magnetic fields at frequencies from 0 to 3 kHz.

Regarding long-term exposures to magnetic fields, the most recent reviews considered in the standard are the following: the International Commission on Non-Ionizing Radiation Protection (ICNIRP) [22], the International Agency for Research on Cancer (IARC) [24], the US

National Research Council (NRS) [39], the US National Institute of Environmental Health Sciences (NIEHS) [20, 40] the Health Council of the Netherlands [41], the Institution of Electrical Engineers [42], and the Advisory Group on Non-Ionizing Radiation (AGNIR) of the UK National Radiological Protection Board [43].

Because none of the above reviews concluded that any hazard from long-term exposure has been confirmed, this standard does not propose limits on exposures that are lower than those necessary to protect against adverse short-term effects. The purpose of this standard is just to define exposure standards for the frequency regime 0–3 kHz. For pulsed or nonsinusoidal fields, it may be necessary to evaluate an acceptance criterion at frequencies outside this frequency regime by means of a summation from the lowest frequency of the exposure waveform, to a maximum frequency of 5 MHz, as detailed in the standard itself [38].

Frequency (Hz)	Magnetic field H (Am⁻¹)	Magnetic flux density B (T)
<0.153 Hz	9.39×10^4	118×10^{-3}
0.153–20 Hz	$1.44 \times 10^4/f$	$18.1 \times 10^{-3}/f$
20–759 Hz	719	0.904×10^{-3}
759 Hz to 3 kHz	$5.47 \times 10^5/f$	$687 \times 10^{-3}/f$

Notes: f is the frequency in Hz; MPEs refer to spatial maximum.

Table 3. IEEE's maximum permissible exposure to sinusoidal magnetic fields for general public: head and torso.

Frequency (Hz)	Magnetic field H (Am⁻¹)	Magnetic flux density B (T)
<10.7 Hz	–	353×10^{-3}
10.7 Hz to 3 kHz	–	$3790 \times 10^{-3}/f$

Note: f is the frequency in Hz.

Table 4. IEEE's maximum permissible exposure to sinusoidal magnetic fields for general public: arms and legs.

In addition to the in situ electric field restrictions collected in the standard, but not discussed in this chapter, the in situ magnetic field below 10 Hz should be restricted to a peak value of 167 mT for the general public and up to 500 mT in a controlled environment. For frequencies above 10 Hz, a basic restriction on the in situ magnetic field is not specified in IEEE's standard. **Table 3** lists maximum permissible magnetic field limits (flux density B, and magnetic field strength H) corresponding to head and torso exposure for general public. The averaging time for a root-mean-square (RMS) measure is 0.2 s for frequencies above 25 Hz. For lower frequencies, the averaging time is such that at least five cycles are included in the average, but with a maximum of 10 s. In the same way, **Table 4** shows arm and leg exposure limits, also for general public. All these maximum exposure limits are based on avoidance of the following short-term reactions [38]:

- Aversive or painful stimulation of sensory or motor neurons.

- Muscle excitation that may lead to injury while performing potentially hazardous activities.

- Excitation of neurons or direct alteration of synaptic activity within the brain.

- Cardiac excitation.

- Adverse effects associated with induced potentials or forces on rapidly moving charges within the body, such as in blood flow.

IEEE's maximum permissible exposure values must be understood in the same way as INCIRP's reference levels. In this sense, compliance with **Tables 3** and **4** ensures compliance with the basic restrictions, which are defined in terms of in-body quantities. However, lack of compliance with these tables does not necessarily imply lack of compliance with the basic restrictions, but rather that it may be necessary to evaluate whether the basic restrictions have been met [38]. For more information, the reader is referred to the standard itself.

The information contained in **Tables 3** and **4** is also shown in **Figure 4** for clarity. Besides, ICNIRP's reference levels for general public are also included in the figure for comparison.
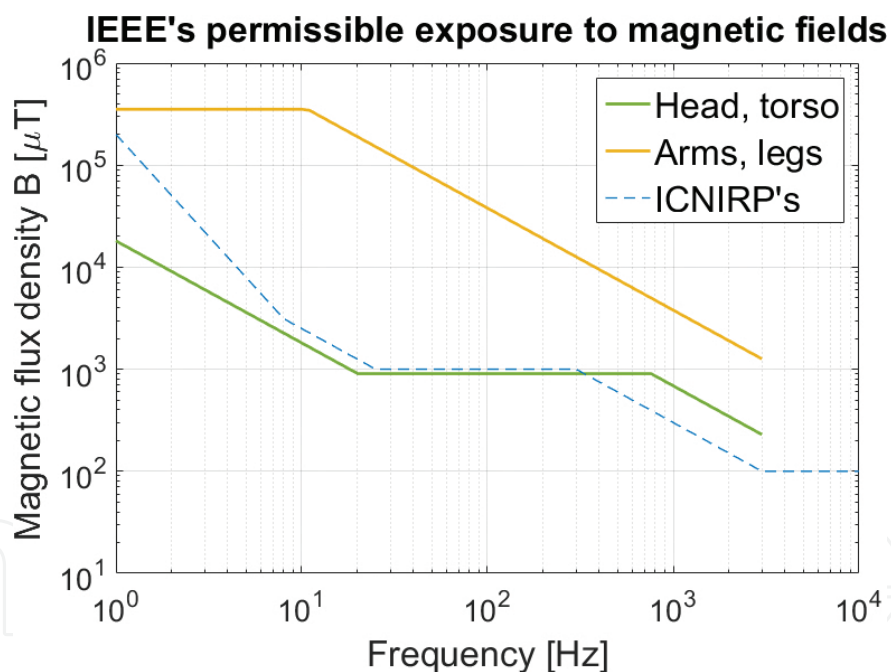

Figure 4. IEEE's maximum permissible exposure to sinusoidal magnetic fields as a function of frequency (up to 3 kHz).

4. State of the art

This section is devoted to a brief overview of recent publications that deal with EMR and magnetic field exposure in EVs. Some main conclusions, drawn for these studies, are sum-

marized here as well. Related publications, such as those that analyze EMC in electric vehicles or EMR in other applications, are also mentioned.

In general, there are not many publications about magnetic field exposure in electric and hybrid cars. Most works about electromagnetic fields and EVs address problems belonging to the field of EMC. Some examples of such studies can be found in [44–48]. There are certainly several publications that deal with EMFs and its potentially hazardous effects on human health, both from the medical and from the engineering points of view, but for other applications. A review of the medical literature is certainly out of the scope of this chapter, and hence the reader is referred to specialized bibliography such as [23–26, 28] for that purpose. Regarding engineer-ing publications, one classical field of study are power lines [49–52], substations, and other transformation centers [49–54]. Most of these works focus on the effects of EMFs on workers (i.e., occupational exposure). Medical equipment in hospitals is another typical example of electromagnetic evaluation, again focusing on the people operating these machines on a daily basis. More recently, some studies have approached electromagnetic exposure from the point of view of general public, for example, in buildings and urban environments [55, 56]. The first studies in vehicles were probably those about electrical trains and trams, and also about conventional ICE-based cars [57–59].

In general, publications about EVs and EMR can be classified into two main groups: studies that perform measurements in vehicles (experimental approach) and studies that use analytical approximations or numerical simulations, usually based on the finite element method (FEM) (simulation approach). These two groups are treated separately in the following sections.

4.1. Magnetic field measurement in electric vehicles

One of the first publications specifically dedicated to EMR in hybrid and electric cars is the one by *ElectromagneticHealth.org* [60], which focuses on the 2004 Toyota Prius (second gene-ration). This preliminary study, which was motivated by a press article published in 2008, titled "*Fear, But Few Facts, on Hybrid Risks*," concludes that it is considerably difficult to perform repetitive and accurate measurements in a moving vehicle without the proper means. The magnetic field values obtained during this study were not high (always below 1 µT), but possibly higher than those found in conventional ICE-based cars. The rear seats were the most exposed, according to this work. One year later, in 2009, two more studies were published which included measurements in an electric car and in a hybrid bus, respectively, under dynamic driving conditions [13, 61].

The next two noteworthy publications, Ref. [58] from 2010 and Ref. [34] from 2013, describe some issues that should be taken into account when measuring magnetic fields in vehicles. The work in Ref. [58] deals mainly with trains and trams, but hybrid cars are also considered. Previous measurements performed in trains, locomotives, and railway stations by different researchers are summarized in that paper. Average results are provided for each type of vehicle considered in the study: 200 trains and trams (both urban and suburban), and also one hybrid car. Train and tram measurements were taken in varied conditions: weekdays and weekends, day and night, inside and outside. Regarding the hybrid car, different positions (front and rear parts, left and right sides, floor, seat, and head levels) were taken into account. Frequency

spectrum ranges from 5 Hz to 100 kHz. Magnetic field values found in the car are low (in the order of a few μT), especially when compared to ICNIRP's reference levels, although it is not clear which method was used to account for multifrequency exposure (see Subsection 3.1). In average, highest magnetic field values were found at the rear left side of the hybrid car. The maximum levels of recorded magnetic field strength are emitted at 12 Hz, which is a very low frequency. About the study published in [34], it provides an example of how to deal with multifrequency exposure in accordance to ICNIRP's recommendations. This work focuses on electric vehicles exclusively, and the magnetic field values obtained are in line with those from [13], around 15–20% of ICNIRP's reference levels. The paper also presents simulation results (see Subsection 4.2).

In 2015, two journal papers were published with measurement results from a wide variety of hybrid and electric cars [9, 10]. Some of their authors participated in the two publications from the previous paragraph. The study in [9] comprises a total of three conventional cars and eight electric vehicles, including some based on fuel cells instead of batteries. Both laboratory measurements and road measurements were taken and compared to INCIRP's reference levels with a wide-frequency range, up to 10 MHz. The vehicle that showed highest values reached 18% of ICNIRP's levels. Unsurprisingly, the researchers found that magnetic field exposure was higher in EVs than in ICE-based vehicles in average. However, the position of maximum exposure within each vehicle (front vs. rear part, foot vs. seat level) was different. This position is probably influenced by the configuration and topology of the vehicle, as described in Section 2. The main sources of magnetic field are identified in this study: at frequencies below 1 Hz, hundreds of μT are present (most likely due to battery current). Between a few Hz and 1 kHz, fields up to 2 μT were found, generated by most sources (combustion engine, steering pump, and wheels are mentioned in the paper, but probably fundamental currents in the inverter and in the electrical machine were also responsible). Finally, above 1 kHz, less than 100 nT was measured, and the authors identified the inverter as the only source (which makes sense, since it is the only power electronics device in the traction drive).

The open-access study in Ref. [10] focuses on diesel, gasoline, and hybrid cars. Up to 10 vehicles are analyzed, and the results are consistent with previous investigations. Results are presented separately for different seats and for different engine types. In general, magnetic field exposure was higher in hybrid cars, and then in gasoline cars. The authors state that magnetic field exposure depends on the operating conditions (speed, acceleration, etc.), which is unsurprising.

4.2. Magnetic field estimation by numeric simulations

Other research projects take a different approach and analyze the problem by means of finite element method (FEM) simulations and even analytical approximations. FEM simulations are helpful to better understand the problem, to analyze magnetic field exposure dependence on certain parameters (for instance, by performing sensitivity analysis), and to develop a predictive methodology. Being able to estimate magnetic field exposure without actually having to perform measurements could prove extremely useful for EV designers. As proposed in Ref.

[62], a fully operational estimation tool would allow for optimized predesign even before building the first prototype, thus reducing engineering time and cost.
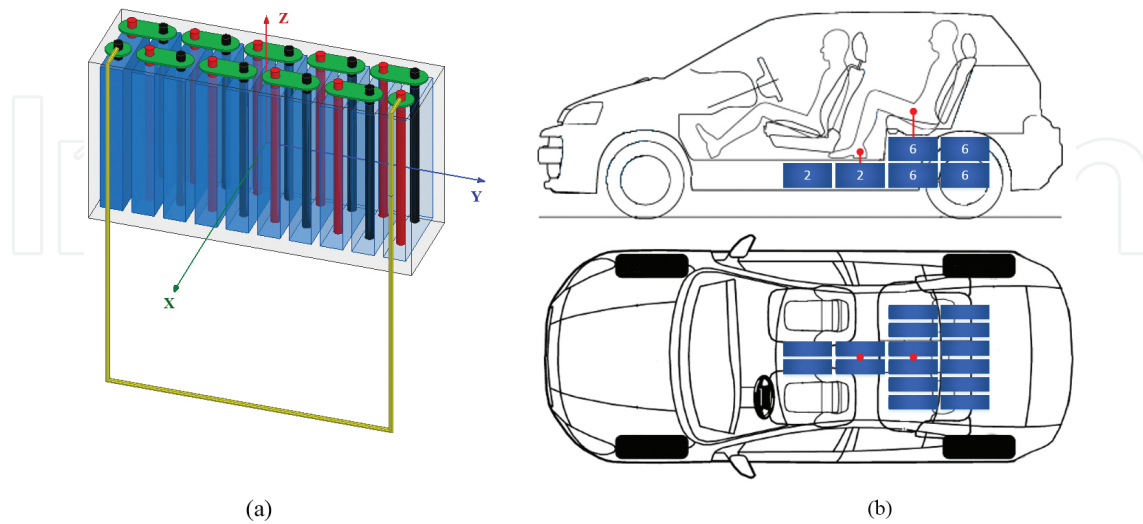

Figure 5. (a) FEM model used in Ref. [64] to estimate the magnetic field generated by one single NiMH battery cell. (b) Hypothetical battery pack belonging to a hypothetical EV analyzed in Ref. [64]. Both figures have been reused with permission.

This is the approach taken in Refs. [63, 64], works that analyze the magnetic field generated by the inverter and by the batteries, respectively, of a hypothetical EV via FEM simulations (**Figure 5**). Simulation results are validated with experimental measurements in both cases, and then they are used to estimate the worst operating points from the point of view of passenger exposure. Similarly, Refs. [14] and [34] contain two examples of how FEM simulations can be used for estimation and prediction purposes (**Figure 5**).

5. Design guidelines

In this section, some design guidelines and recommendations to minimize magnetic field exposure in EVs are provided. Note that all these measures are of pure electric nature, and therefore they may not be applicable when considering other factors. They are based on the ALARP principle ("As Low As Reasonably Practicable"). In other words, the goal is to maintain exposure levels as low as reasonably possible with the available means, both in a technical and in an economic sense. This criterion allows the implementation of safety strategies at an acceptable cost, and it should preferably be applied during the first design stages of the EV and its components.

These guidelines are classified into two groups, depending on whether they involve major changes in the vehicle or not. The first group contains measures that do not change the topology nor the configuration of the vehicle, and that do not increase its weight nor its cost:

- A general design guideline is to place the power devices and their connections as far from the passengers as possible. However, a vehicle usually provides little room to maneuver in this sense, especially in the case of hybrid electric vehicles. The battery stack, the electronic converters, and the motor should be as far away as possible from the passengers. Batteries are usually placed just under the seats, in order to minimize risks in case of crash. However, this involves bringing them closer to the passengers. A compromise should be reached.

- Complementary, power devices should be oriented so that the magnetic field suffered by the passengers is minimized. As described in Section 4, some power equipment such as batteries and inverters could generate stronger fields in some specific directions [63, 64]. Therefore, their relative direction with respect to the passengers should be carefully chosen.

- Wires of the same type should be as close as possible of each other: both DC wires must be taped together; similarly, the three-phase AC wires must be taped together, preferably in a triangular disposition. This way, the magnetic field generated by each cable in the interior of the vehicle will be cancelled by the rest.

- Wires should be as short as possible, except when this involves bringing them closer to the passengers.

- When placing batteries below the seats, the battery pack can be redesigned in order to allow terminals to be placed at the bottom. This would increase the distance from the stack connections to the passengers in a value equal to the height of the battery cells. This is very convenient, given that those connections are usually close to the occupants, they carry currents up to hundreds of amperes, and it is very difficult to place them together so the magnetic field generated by all of them as a whole is cancelled out. Naturally, the chemistry of the batteries must allow this inverted position, which is not a problem with lithium-based technologies. Notice that this action does not necessarily increase the distances between the passengers and the cells themselves.

If further actions were necessary in order to reduce the magnetic field generated by the EV, these additional measures may prove helpful:

- Longer distances between power equipment and passengers are always welcome. As discussed in Section 2, front-wheel traction drives are usually better suited to provide such longer distances.

- In the same sense, in-wheel motor technology [65] allows the devices inside an EV to be distributed in a much more flexible way. The space reserved for the conventional internal combustion motor could be occupied by the battery stack instead, which would mean that no field-generating devices would be placed under the seats.

- The higher the voltages, the lower the currents and the magnetic field, but the electric field could become higher (considering a quasistatic approximation [8], higher voltages, and higher du/dt will imply higher Coulomb electric field, but lower currents involve lower magnetic fields and thus lower Faraday electric field during transients [62]). Nonetheless, high on-board voltages may be hazardous in case of a crash, so once again a compromise would be necessary.

- A magnetic shield can be placed around the main devices responsible for the magnetic field in the interior of the car. Alternatively, the whole interior could be shielded, yielding higher protection at the expense of increased shield weight and cost. In both cases, the efficacy of the shield will be determined by its properties, and especially by its thickness. In the first case, a ferromagnetic alloy of high magnetic permeability, such as Mu-metal or similar, could be used [66]. For shielding the whole interior, ferromagnetic sheets such as those used to shield hospital rooms and some laboratories are recommended instead [67]. Notice that if switching frequencies grow above 100 kHz (by using SiC power devices, for instance), Faraday shielding could become necessary. This consist in radiofrequency shields made of copper or similar [67], such as those found in microwave ovens.

6. Discussion

Magnetic field exposure is a matter of growing concern in the society. Recently, low-intensity exposure is receiving much attention due to its possible hazardous effects on human health in the long term. However, uncertainty is high and there is still much research to be done. In this sense, short-term effects are proven and well known, while long-term effects remain to be found (although some theoretical bases and some experimental results point to the existence of potential hazardous effects [23]). With respect to EVs in particular, results presented so far in the scientific literature suggest that this concern is not scientifically justified, at least according to current standards and guidelines, which only take short-term exposure into account. In general, exposure levels in EVs are low when compared to ICNIRP's and IEEE's recommended levels, but high when compared to other daily exposures such as those suffered at home or at work. This increase in overall magnetic field exposure is what generates concern, despite the lack of scientific proof.

Uncertainty is not the only worrying aspect of magnetic field exposure in EVs. Some emerging and promising technologies, such as SiC power electronics, could pose a significant threat, given that they allow for higher switching frequencies. Certainly, there are many aspects involved, and therefore deep analysis is required before drawing any conclusions. However, it is clear that replacing silicon-based IGBTs with SiC MOSFETs could change the spectrum of the magnetic field inside the vehicle drastically, for better or for worse. In this sense, there are already a few publications that alert about a worsening in EMC phenomena when using SiC technology [68].

Paradoxically, some scientific results suggest that low-intensity low-frequency magnetic fields could have beneficial effects on human health. Certainly, these usually refer to medical treatments based on EMFs, but still knowledge is scarce about what will happen to EV passengers in the long term. Other experts have mentioned that even if magnetic fields have undesired effects on humans, it is perfectly possible that our bodies have inbuilt mechanisms to compensate for these effects [23]. Once again, further research is needed.

Finally, the authors would like to state that driving style has a strong influence on magnetic field exposure. In this regard, those drivers that favor aggressive styles (strong accelerations

and deep regenerative braking) will be exposed to stronger magnetic fields. Efficient driving does not only reduce fuel consumption and maintenance needs; it also reduces magnetic field exposure.

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