Car, electric car, hybrid car

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Electric and magnetic fields can occur in cars with combustion engines, electric cars and hybrid cars. They have various causes:

- in electric cars and hybrid cars, the electric drive and the battery mainly generate magnetic fields.
- In cars with combustion engines and hybrid cars, the fuel pump, generator (alternator) and battery mainly generate magnetic fields.
- in all types of cars, the on-board electrical and electronic systems, such as wiring, air conditioning, seat heating, entertainment and navigation devices, driver assistance systems and sensors, generate electric and magnetic fields.
- In all types of cars, mobile telecommunications generate electromagnetic radiation.
- In all types of cars, magnetic fields are generated by the steel belts in the tyres. These consist of steel wires, which are magnetic. The rotating wheels generate magnetic fields inside the vehicle.

The magnetic fields generated by cars with combustion engines, electric cars and their charging cables or hybrid cars comply with the limits designed to prevent short-term health effects. Based on current knowledge, it is not possible to assess the extent to which these fields affect health in the long term.

The electromagnetic radiation generated by mobile phones or other radio applications inside the car also complies with the limit values. However, drivers are only allowed to use mobile phones with a hands-free device. Please note that the risk of an accident is increased even when using a hands-free device.

People who want to minimise exposure as a personal precaution can do so by following the tips below. There are no further optimisation options for any type of car.

- You can have your car tyres permanently demagnetised at some specialist garages.
- If possible, do not set the seat heating to maximum in order to reduce exposure to magnetic fields in the abdominal and back areas.
- Refrain from making phone calls or reading or writing messages while driving. Please note the information provided by the BfU on the legal consequences of using a mobile phone while driving: what is permitted – and what is not | BFU. If, despite everything, you do not want to refrain from making phone calls in the car, be sure to use a hands-free device.

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Detailed information

1 Limit values

The International Commission on Non-Ionising Radiation Protection (ICNIRP) assesses the health effects of electromagnetic fields. It issues recommendations for limit values [1], which in turn form the basis for the limit values in the EU Council Recommendation [2]. The EU limits define the basic requirements that electrical products must meet in Europe and Switzerland in order to be considered safe in terms of their electromagnetic fields.

These limits are based on scientifically proven acute effects in humans when the fields exceed a certain strength. The limits for the general population are 50 times lower than the value at which acute effects occur.

There are two categories of limits: so-called basic restrictions and reference levels derived from them. Depending on the frequency range, they have different values or represent different physical quantities.

1.1 Low-frequency and medium-frequency fields

The basic restrictions in the low-frequency range refers to electric currents that generate magnetic fields in the body (body currents). These currents can have an acute effect on the functions of the nervous system. Since these body currents cannot be measured directly, reference levels derived from the basic restrictions are used in practice. They can be measured as an electric or magnetic field in the absence of the person. If the reference levels for magnetic fields are complied with, the current in the body of an exposed person is usually also below the basic restrictions. However, if the reference levels are exceeded, complex methods such as computer simulations of human models must be used to check whether the basic restrictions are complied with.

1.2 High-frequency electromagnetic radiation

A person's body can absorb high-frequency electromagnetic radiation and heat up as a result. Limit values restrict this heating so that no health risks arise.

Basic restrictions for frequencies up to 10 GHz are the specific absorption rates (SAR values). They indicate how much electromagnetic radiation (expressed as radiation power in watts) a certain mass of the human body (kg) absorbs. They depend on whether the radiation affects the entire body, the limbs, the head or the torso. The limit value for the torso and head is the most stringent and is 2 W/kg, averaged over a body volume of 10 grams. This means that in the most heavily irradiated body volume of 10 grams, the SAR must not exceed 0.02 W/kg. SAR values are best used to assess devices that people typically use on the surface of the body or in close proximity to the body.

Since radiation at frequencies above 10 GHz no longer penetrates deep into the body, the tissue only heats up near the surface or on the surface of the body. The basic restrictions for radiation with frequencies above 10 GHz, such as that emitted by radar systems, are based on the power density in

W/m^2.

SAR values are difficult to determine. The reference levels derived from them are much easier to measure. However, they are only applicable to homogeneously irradiated bodies. They refer to electric and magnetic fields, magnetic flux density and power density.

1.3 Limit values and long-term effects

Potential long-term effects are not taken into account in these recommended limits. The reason for this is that the ICNIRP considers the scientific evidence for harmful effects of long-term exposure to electromagnetic fields to be insufficient.

2 Low and medium frequency fields in cars

2.1 Causes

2.1.1 Cars with combustion engines

In cars with combustion engines, various electrical systems and devices require electrical energy. When the car is stationary, this energy is supplied by the battery, and when the car is moving, it is supplied by the generator, which converts mechanical energy into electricity. The electricity usually flows through wiring to the individual systems and back to the battery or generator via the car body, which acts as a neutral conductor. This generates low-frequency magnetic fields.

2.1.2 Electric cars

Electric cars are powered by an electric motor. Unlike cars with combustion engines, they can convert or recuperate some of the energy generated during braking into electrical energy. In this operating mode, the moving car drives the electric motor, which now functions as a generator or motor brake. Depending on the route, the electric motor constantly switches between motor mode, which consumes energy, and generator mode, which produces energy. A battery stores the electrical energy generated during braking. Due to its large size, the battery is often installed in the vehicle floor.

The current usually flows through wiring to the electric motor and other electrical systems and back to the battery via the car body, which serves as a neutral conductor. This creates magnetic fields. As the cables and battery are located close to the passenger compartment, there is a possibility that some of the fields may penetrate the passenger compartment.

2.1.3 Hybrid cars

Hybrid cars are mainly powered by a combustion engine, which is supported by an electric motor. When braking, the electric motor can act as an engine brake or generator and generate electrical energy that is stored in a battery. This is usually installed in the boot floor or under the rear seat. Plug-in hybrid cars can also charge the battery via an external power supply.

2.2 Size of magnetic fields

A 2025 study commissioned by the German Federal Office for Radiation Protection measured the magnetic fields in 11 different electric cars, two hybrid cars and one car with a combustion engine [3]. The results are summarised in Table 1. The table shows the percentage utilisation of the reference levels on the most exposed seats of 11 electric cars, two hybrid cars and one car with a combustion engine. If a situation (e.g. highest magnetic field on the driver's seat) affects several vehicles, the ratio of the reference level utilisation of the most and least exposed vehicles is also given.

	Maximum reference level utilisation						
Seat with highest magnetic fields	Electric cars (11 vehicles)			Hybrid cars (two vehicles)			One car with a combustion engine
	Number of vehicles affected	Maximum utilisation [%]	Ratio between the most and least polluting vehicles (rounded)	Number of vehicles affected	Maximum utilisation [%]	Ratio between the heaviest and lightest loaded vehicle (rounded)	Maximum utilisation [%]
Driving at a constant speed							
Driver's seat	5	62	10 to 1	2	101	3 to 1	24
Passenger seat	5	19	3 to 1	-	-	-	-
Rear seat	1	11	-	-	-	-	-
Accelerating							
Driver's seat	6	66	8 to 1	2	1200	33 to 1	79
Passenger seat	4	123	18 to 1	-	-	-	-
Rear seat	1	30	-	-	-	-	-
Braking							
Driver's seat	6	282	26 to 1	-	-	-	109
Passenger seat	4	320	11 to 1	2	137	5 to 1	-

Rear seat	1	77	-	-	-	-	-
Standstill							
Driver's seat	5	425	4 to 1	1	305	-	576
Passen-ger seat	6	704	12 to 1	1	1500	-	-
Rear seat	-	-	-	-	-	-	-

Table 1: Magnitude of magnetic fields on the most exposed seats as a percentage of the reference level [3]. If a situation (e.g. highest magnetic field on the driver's seat) affects several vehicles, the rounded ratio of the reference level utilisation of the most and least exposed vehicles is given.

The study shows

- that both the car with a combustion engine, the two hybrid cars and the electric cars can generate magnetic fields which, in individual situations, can briefly and locally reach or exceed the reference levels.
- that the highest magnetic fields that occur are vehicle specific.
- that the seats where stronger magnetic fields occur inside the vehicle are also vehicle specific.
- that magnetic field exposure in the foot and leg area of the driver's seat tends to be greater than in other parts of the body, such as the upper body.
- that magnetic field exposure during acceleration and braking in electric and hybrid cars tends to be significantly higher than when driving at a constant speed.
- that the magnetic fields, which in some cases exceed the reference levels, always comply with the basic restrictions. The study assessed the results in accordance with the ICNIRP restrictions of 2010 [23] for exposures that do not affect the central nervous system. The latter are not intended for use in the EU and Switzerland to assess product safety.
- that, according to current knowledge, people with implants are not at risk from magnetic field exposure.

The study also shows that magnetic fields not generated by the electric drive (e.g. when the vehicle is stationary or in cars with combustion engines) can reach higher values. They are caused by electrical components that switch on and off, such as:

- when the car is switched on.
- seat heaters that regulate their temperature with unfavourable switching controllers. The lower abdomen and back area are particularly affected.
- when indicating.
- by fans in the interior.

– window regulators.

2.3 Magnetic fields during electric car charging

A study conducted by the German Federal Office for Radiation Protection [4] examined the magnetic fields generated inside electric cars during charging and outside, around typical European charging stations or facilities. Table 2 lists the main types of charging (charging modes) used in Switzerland and the corresponding charging facilities.

Charging mode Charging device	Current	Voltage	Maximum charging power	Cable plug type	
				Vehicle side	Mains side
Charging mode 2 Charging cable with plug connection for - domestic use - industrial	alternating current single-phase - 8 A - 16 A	- 230 V - 230 V	- 1.8 kW - 3.7 kW	- 2 - 2	- Type 13 - CCE 16/3
Charging mode 3: - Wall-mounted box - Charging terminal	Single-phase to three-phase alternating current - 16 A - 32 A	- 230 V - 400 V	- 3.6 kW - 22 kW	- 2 - Combo 2	2
Charging mode 4: Charging station	Direct current	- 150-400 V - 150-800 V	- 150 kW - 300 kW	Combo 2	Fixed cable at the charging station
Inductive: coil in the ground or car park beneath the vehicle. Coil in the vehicle	Alternating current		Experimental up to 22 kW	Not available	Not available

Table 2 Overview of common charging types (charging modes) in Europe for charging an electric car. Data adapted for Switzerland.

Table 3 shows the magnetic fields generated inside electric cars during charging. The values are given as a reference value for the following points.

– Charging mode
– Seat measured
– Time: at the start of charging (2 to 5 s) or during stationary charging (from 10 s)
– Remaining battery charge: battery almost completely discharged (10%) or battery almost completely charged (>95%)

Charging mode 2; AC alternating current Maximum reference usage value [%] of two vehicles on a charging cable connected to a socket with a charging power of 2 kW			
Seat	Remaining battery charge		Maximum exposure point
	10	>95%	
Driver's seat; Start of charging	51	26	Footwell
Driver's seat; Stationary charging	4.4	2.8	Footwell
Passenger seat; Start of charging	0.9	1	Footwell
Passenger seat; Stationary charging	0.8	0.9	Footwell
Charging mode 3; Alternating current AC Maximum utilisation values of reference values [%] for six vehicles on an AC wall box with a charging power of 11 kW			
Driver's seat; Start of charging	219	133	Footwell
Driver's seat; Stationary charging	5	3.7	Footwell
Passenger seat; Start of charging	89	100	Footwell
Passenger seat; Stationary charging	3.5	2.5	Foot area
Charging mode 3; Alternating current AC Maximum usage values of reference values [%] for six vehicles at a 22 kW charging station			
Driver's seat; Start of charging	190	208	Footwell
Driver's seat; Stationary charging	4.6	5.8	Footwell
Passenger seat; Start of charging	139	147	Footwell
Passenger seat; Stationary charging	2.2	2.1	Footwell
Charging mode 4; Direct current DC Maximum utilisation values of reference values [%] for two vehicles at two DC charging stations with charging powers of 300 and 350 kW			
Driver's seat; Start of charging	26	26	Front seat footwell
Driver's seat; Stationary charging	<0.8	<0.8	
Passenger seat; Start of charging	8	2.5	Rear seat lower section
Passenger seat; Stationary charging	<0.8	<0.8	

Table 3 Magnetic fields inside the vehicle during the charging process with different charging modes

Table 4 shows the magnetic fields generated outside electric cars during charging. The values are given as a reference value based on the following points.

- Charging mode

- In the immediate vicinity of the socket, as well as near the charging station and the vehicle connection
- Time: at the start of charging (2 to 5 seconds) or during stationary charging (from 10 seconds)
- Remaining battery charge: battery almost completely discharged or battery almost completely charged

Charging mode 2; alternating current AC Maximum reference usage value [%] of two vehicles on a charging cable connected to the socket with a charging power of 2 kW				
Position	Remaining battery charge			
	10		>95	
	Start of charging	Stationary charging	Start of charging	Stationary charging
Distance of 30 cm from the vehicle connector	3.5	0.9	4.6	<0.8
Connector on the vehicle	260	28	286	25
Charging mode 3; Alternating current AC Maximum utilisation values of reference values [%] for six vehicles at an AC wall box with a charging power of 11 kW				
Distance of 30 cm from the vehicle connection	10	0.9	15	<0.8
Connector on the vehicle	1700	161	1510	131
Distance of 30 cm from the wall box	5.1	<0.8	4.9	<0.8
Charging mode 3; Alternating current AC Maximum utilisation values of reference values [%] for six vehicles at an AC charging station with a charging power of 22 kW				
Distance of 30 cm from the vehicle connection	56	5.2	50	5
Connector on the vehicle	1740	154	1460	139
Distance of 30 cm from the charging station	8.2	0.9	8.5	0.9
Charging mode 4; Direct current DC Maximum utilisation values of reference values [%] for two vehicles on two DC charging stations with charging powers of 300 and 350 kW				
Distance of 30 cm from the vehicle connection	2.7	2.7	2.2	1.1
Connector on the vehicle	99	99	118	30
Distance of 30 cm from the charging station	8	8	6	6

Table 4 Magnetic fields at charging stations during the charging process with different charging modes

The results concerning the use of reference values show that, for all charging modes

- in most cases, the fields at the charging devices and in the vehicle are below the reference values.
- high values, exceeding the reference values, can often occur at the vehicle connectors.
- high values occur at the start of charging and at the vehicle's footwell.
- the fields do not depend on whether the battery is almost empty (10% charge remaining) or almost full (charge remaining > 95%) at the start of charging.

As the reference values were partially exceeded, the study used a computer simulation to verify whether the basic restrictions were respected. The results for two vehicles in which the reference values were exceeded show that the basic restrictions are respected in all cases. Their use is

- less than 2% for a person sitting in the driver's seat.
- less than 15% for a person standing near the vehicle connector, with children potentially exposed to higher levels than adults.
- less than 15% (according to ICNIRP 2010 [23]) for a person holding a charging plug or less than 30% if holding the cable.

The study also examined the fields generated by a pilot wireless induction charging installation for taxis. Two vehicle positions were examined

- The vehicle is centred on the activated charging device
- The vehicle is offset by 12 cm to the side of the activated charging device

The results show

- that the reference value inside the car is used at around 20%, with slightly higher usage when the car is offset from the charging device.
- that the reference value is significantly exceeded just next to the vehicle up to a height of 40 cm above the ground, i.e. up to 400% when the vehicle is centred and up to 600% when the vehicle is offset.
- that the basic restriction, on the other hand, is used at less than 1% inside the car and less than 2% outside the car.

2.4 Magnetic fields from car tyres

2.4.1 Cause / Magnitude

The steel inserts in car tyres are magnetised during the manufacturing process. When the car is stationary, they generate a static magnetic field, and when the car is moving, they generate a low-frequency magnetic field. The frequency of the magnetic field depends on the speed of the car. A study funded by the FOPH investigated the magnetic fields generated by magnetised car tyres in twelve different cars. The measurements were taken at a speed of 80 km/h. This resulted in low-frequency magnetic fields with frequencies between 5 and 2000 Hz (Table 5) [5].

Magnetic field (μT)	Driver's pelvic area	Driver's head area	Passenger's foot area	Rear seat
Average	0.29	0.21	3.22	3.28
Standard deviation	0.18	0.10	2.53	2.55
Maximum	0.73	0.45	8.89	9.51
Minimum	0.12	0.10	0.76	0.65

Table 5: Peak values in the magnetic field spectrum at various positions in twelve cars travelling at 80 km/h [5].

High values were measured in the footwell of the front passenger seat and on the rear seat. Values above 2 μT were measured in two-thirds of the cars, and values above 6 μT in a quarter of the cars.

The fundamental frequency of the magnetic fields is 10–12 Hz at a driving speed of 80 km/h. Figure 1 shows, however, that higher harmonic frequencies are also measured.

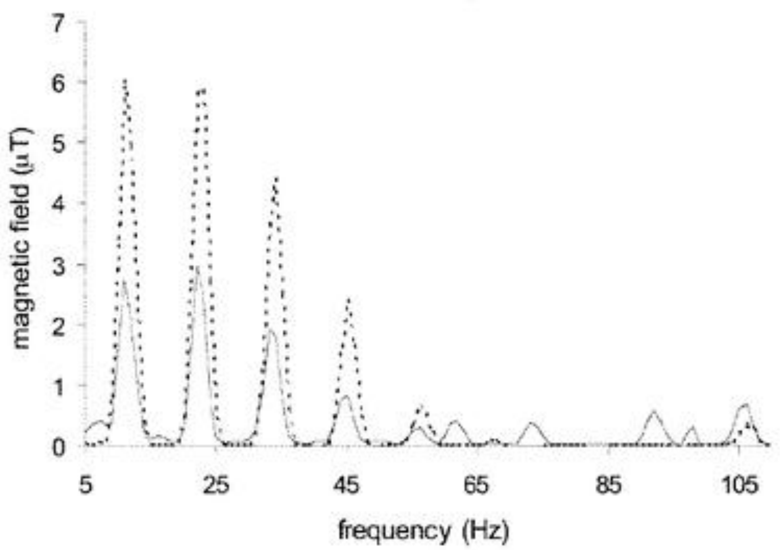

Figure 1: Typical magnetic field spectrum in a car travelling at 80 km/h (magnetic field as a function of frequency). Dashed line: foot area of passenger seat, solid line: rear seat. [5]

A weighted sum of the spectral magnetic field components between 5 and 100 Hz shows that, on average, 4% and a maximum of 6.9% of the reference level is reached in the rear seat of the twelve cars measured (Table 6).

Utilisation of the reference level	Passenger footwell	Rear seat
Average	4.6	4.0
Maximum	14.3	6.9
Minimum	1.0	0.4

Table 6: Weighted sum of spectral magnetic fields in the passenger compartment of twelve moving cars. 100% corresponds to the full utilisation of the reference level [5]

The same study examined the magnetic fields of 32 individual car tyres on rims at a distance of 2 cm from the wheel on a balancing machine (Table 7). The frequency of the magnetic fields ranged between 5 and 2000 Hz and depended on the speed of the balancing machine. The magnetic fields of the car tyres measured show a wide variation between 0.8 and 97 μT.

Magnetic field (μT)	All car tyres (n=32)	New car tyres (n=13)	Used car tyres (n=19)	Alloy wheels (n=25)	Steel rims (n=7)
Average	25.2	22.4	29.2	21.5	38.1
Standard deviation	22.3	7.8	34.0	18.8	29.9
Maximum	97.0	33.9	97.0	97.0	71.9
Minimum	0.8	10.1	0.8	0.8	6.4

Table 7: Peak values of the spectral magnetic fields of car tyres, measured on a balancing machine at a distance of 2 cm from the car tyre surface [6].

2.4.2 Demagnetisation of car tyres

Another aim of the FOPH study was to build a practical device that could be used to demagnetise car tyres [6]. This was achieved using a conventional wheel balancing machine on which a car tyre rotates on a rim. A movable holder positions an electric coil very close to the car tyre. The holder then slowly moves the coil, which generates a strong 50 Hz magnetic field, away from the wheel. This continuously reduces the magnetic field around the car tyre, demagnetising it. This method made it possible to permanently reduce the magnetic fields of car tyres significantly [6] (Table 8). Even after five months of use, the magnetic fields were still greatly reduced.

Tyre condition	Magnetic field (μT)
Before demagnetisation	11.7 ± 3.1
After demagnetisation	1.5 ± 1.6
Check after 1 month	1.1 ± 0.9
Check after 5 months	1.4 ± 1.5

Table 8: Peak values of the magnetic fields of four car tyres, measured on a balancing machine at a distance of 2 cm from the car tyre surface. Control measurements after 1 and 5 months of use of the car tyres [6].

Some garages in Switzerland offer tyre demagnetisation services https://www.mensch-und-technik.ch/mut/Autoreifenentmagnetisierungsger%C3%A4t/Standortliste%20Autoreifenentmagnetisierung_1.pdf

3 High-frequency electromagnetic radiation inside cars

3.1 Mobile telephony

3.1.1 Exposure from external vehicle antennas

Several studies have investigated the exposure inside vehicles to radiation from antennas mounted outside the passenger compartment [7]. The antennas investigated used different frequency bands such as VHF, UHF, GSM, 5G NR and WI-FI. The studies show

– that exposure in the passenger compartment was below the reference levels for the respective frequency bands
– that the SAR values were lower than the basic restrictions.
– That the highest exposure was observed on the whole body and in the head area.

3.1.2 Exposure from in-vehicle antennas

Mobile phones used by people in vehicles connect to the nearest mobile phone base station via their own antenna in most modern cars. Since the enclosed passenger compartment of cars, which consists of windows, steel and plastic, acts as insulation for this connection, higher transmission power from the mobile phone is required. This leads to higher radiation levels inside the car compared to outside [8, 10, 11]. According to the manufacturer's specifications, these higher radiation levels can be reduced in vehicle models that can connect to mobile phone base stations via an external antenna integrated into the vehicle. Studies conducted on this topic [7] show that, overall

– that the radiation from mobile phones, Bluetooth and Wi-Fi devices complies with the reference levels.
– that SAR values depended slightly on the number of occupants and the number of devices in use at the same time but were below the basic restrictions.

An older study examined dosimetric models of adults and children exposed to radiation from UMTS, WiMax and Bluetooth in a virtual realistic car. According to the results, in all scenarios the specific absorption rate (SAR) for the whole body was at least 40 times lower than the limits and the SAR for local exposures was at least 10 times lower [9].

Another older study using the GSM mobile communications standard shows that a person who makes a phone call in a car rather than outdoors is exposed to 5% more radiation (SAR value). Other people in the car are exposed to radiation amounting to up to 40% of the SAR value of the person using the mobile phone [10, 11].

3.2 Radio systems for connected vehicles (V2X)

3.2.1 Technology

So-called V2X (vehicle to everything) systems connect cars via radio with other road users, traffic infrastructure or the internet.

Modern cars are equipped with the V2N (vehicle to network) system. This allows the car to connect to a cloud via mobile communications. The purposes of V2N include data transmission for emergency call systems, navigation systems, traffic information, remote diagnostics, vehicle status queries and software updates by the car manufacturer. This system can transmit data both during operation and when inactive.

Other V2X systems with different purposes are still in the planning or testing stages in some cases but are not yet in widespread use in Europe.

– A V2I (vehicle-to-infrastructure) system connects traffic infrastructure such as traffic lights or road signs with the vehicle in operation.
– A V2V (vehicle-to-vehicle) system connects neighbouring vehicles that are in operation with each other.
– A V2P (vehicle-to-pedestrian) system aims to protect pedestrians from accidents involving cars. It detects pedestrians using on-board systems such as cameras, radar, lasers or sensors, or via a V2P app on the pedestrian's switched-on mobile phone. It transmits to vehicles that are in operation.
– A V2G (Vehicle-to-Grid) system uses intelligent bidirectional charging to enable a parked electric car to operate both as an energy storage device and as an energy supplier in order to cushion excess energy peaks in the power grid.

All these systems require antennas in the car, some of which transmit and thus generate high-frequency radiation inside the car depending on their position. The following technologies are used (Table 9)

– ITS-G5 – Intelligent transport systems, a Wi-Fi adapted to cars that can only communicate directly with other road users or the transport infrastructure (ad hoc).
– C-V2X – Cellular V2X, a modern extension of 4G and 5G mobile communication adapted to cars with the same purposes, but which can also access the internet. It is currently being introduced.

Vehicles that communicate directly with each other send information to each other in what are known as corporate awareness messages (CAM) [12]. These are small data packets containing information on the current time, position, speed, direction of travel, vehicle length, vehicle width, longitudinal acceleration, road curvature, yaw rate, activated systems, etc. of the respective vehicles. The number of messages per second depends on how quickly or significantly this information changes. CAMs result in pulsed electromagnetic radiation.

Technology	Transmission power	Frequency	Frequency of the CAM	Range
ITS-G5 (WI-FI IEEE 802.11p)	Max approx. 2 watts Typically, 0.2 W [13]	5.855 GHz to 5.925 GHz	1-10 per second	Several hundred metres, reduced in case of poor connection quality, e.g. due to obstacles such as buildings or electromagnetic interference
C-V2X or 4G or 5G mobile communications for direct communication between vehicles without a mobile communications base station	Max approx. 0.2 watts [7, 13]	5.855 GHz to 5.925 GHz		
4G/5G mobile communications (C-V2X) for communication via mobile base station	Max approx. 0.2 watts	All mobile communications frequencies	None	Corresponds to mobile network coverage

Table 9: Properties of V2X systems [7]

3.2.2 Exposure from ITS-G5 radio systems for connected vehicles

Various studies have investigated exposure from ITS-G5 antennas. One study determined exposure from ITS-G5 antennas mounted either on the roof or on the upper driver-side corner of the windscreen inside the vehicle [14]. The antenna on the windscreen produced the highest exposures, which were around 15% of the reference level directly in front of the antenna and less than 4% of the reference level on the dashboard, driver's seat and rear seat. The roof-mounted antenna generally resulted in lower exposures, which were 8% directly in front of the antenna and less than 0.5% of the reference level inside the vehicle. The lower values inside the vehicle are due to the shielding effect of the car body. Another study [13] came to similar conclusions. It determined the exposure levels of ITS-G5 antennas mounted either on the rear window or in the front section of the roof. The exposure levels in the head and torso areas of the driver's and front passenger seats as well as the rear seats were around 1% or less of the reference level. Another study used a numerical vehicle model to investigate the SAR values generated by four ITS-G5 antennas on the driver's seat [15]. In one scenario, they were mounted on the rear-view mirrors and in the middle of the roof near the windscreen and rear window. In a second, less optimal scenario, the roof antennas were installed near the head area of the driver's seat. The results show that the basic restrictions were complied with in both scenarios, even when all antennas were in operation. The highest value of 1.58 W/kg occurred in the head area of the driver's seat.

3.3 Other radio systems

Modern cars have a variety of radio systems that enable comfortable and safe operation of the vehicle. Table 10 shows a non-exhaustive list of such radio systems.

Technology	Application	Transmission power [watts]	Frequency band	Study
Short range devices (SRD) Radio frequency identification (RFID)	– Keyless opening, locking and starting of a car by radio, consisting of a transmitter and receiver unit in the car and a transponder (e.g. card) carried by a person. – Vehicle identification systems – Smart parking system – Wall boxes for electric vehicles authentication and start of charging – Authorised access to buildings, car parks or charging stations – Tracking of goods in logistics – Toll systems	0.01- 2	0.027-5.815 GHz	[14]
Analogue and digital radio and television reception	AM, FM, DAB, DVB-T	Reception only		[14]
Global navigation satellite system	GPS, Galileo, BeiDou, GLONASS	Reception only	1,164–1,591 GHz	[14]
Bluetooth	Communication, data transfer including over-the-air updates of software and infotainment.	0.1	2.4-2.4845 GHz	[14]
WI-FI	Communication, data transmission including over-the-air updates of software and infotainment.	0.025-1	2.4-5.725 GHz	[14]
Vehicle radar systems	Long-range radar LLR (up to 150 m range)	0.1	21.650-81 GHz	[14]

	Short-range radar SRR inside mirrors or tailgate (blind spot monitoring, parking aids, etc.)	0.01 – 0.2		
Keyless access Immobilisers	Keyless access	approx. 0.01	– Vehicle 125 kHz – Key 434 MHz	[16]
Bluetooth low energy (BLE)	– Mobile phone that connects to infotainment system – Multimedia systems inside the vehicle – Smart car access – Vehicle diagnostics – Vehicle settings	0.1	2.400 -2.4835 GHz	[7]
UHF Short range	– Tyre pressure monitoring system (TPMS) – Keyless opening, locking and starting of a car by radio signal)	– 0.01 – 0.025	– 434 MHz – 868 MHz	[7]
UWB communication, i.e. a broadband radio technology	Keyless opening, locking and starting of a car via radio	0.07413 µW in any 1 MHz wide section of the occupied frequency band	– 3.1-4.8 GHz – 6-9 GHz with a bandwidth of ≥ 500 MHz or ≥ 20% of the carrier frequency (centre frequency of the frequency band used)	[7]
Near field communication (NFC)	– Keyless opening, locking and starting of a car via radio – Bluetooth/Wi-Fi pairing with the infotainment system	Limitation via the magnetic field	13.56 MHz	[7]

Table 10. Other communication technologies inside cars

There is little information available on the exposure generated by these radio systems inside cars [14]. The available results show that Bluetooth and Wi-Fi devices installed in cars exceed the reference level in the driver's area and in the back seat by less than 2%.

4 Health effects

There are no studies that have directly investigated the health effects of low- and high-frequency electromagnetic fields in cars, electric cars and hybrid cars. These fields must therefore be assessed on the basis of limit values [2].

Magnetic fields can penetrate the body and generate electric currents there. If these currents exceed a certain value, they may acutely excite the nerves of the central nervous system. To prevent this, the limit values are defined so that these currents are at least 50 times lower than this value. Measurements carried out to date have shown that, with a few exceptions, the magnetic fields inside cars, electric cars and hybrid cars comply with the reference levels and, in any case, comply with the basic limit, so that no acute health effects are to be expected. In 2002, the International Agency for Research on Cancer (IARC) classified static and low-frequency magnetic fields as possibly carcinogenic (Group 2B) [17]. This is based on epidemiological studies that suggest that long-term and permanent exposure to magnetic fields in the low dose range from 0.4 μT can increase the risk of developing Alzheimer's dementia [18, 19] or childhood leukaemia [20, 21]. The extent to which low-frequency magnetic fields in cars contribute to such long-term exposure cannot be estimated.

High-frequency radiation is absorbed by tissue and can increase its temperature. If this temperature exceeds a certain value, detectable acute health effects can occur. According to current knowledge, the high-frequency radiation generated by both V2X systems and other radio systems in cars is far too weak to cause such health effects. In 2011, the International Agency for Research on Cancer (IARC) classified high-frequency electromagnetic fields as possibly carcinogenic (Group 2B) [22]. However, this was based on studies showing a possible link between using mobile phones or cordless phones and the occurrence of brain tumours. The IARC considers the data to be limited, as these studies are flawed in terms of their design. Furthermore, the IARC has not found any link between health effects and the high-frequency radiation generated by other categories of devices.

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