Exposure to RF Electromagnetic Fields in the Connected Vehicle: Survey of Existing and Forthcoming Scenarios

GABRIELLA TOGNOLA¹, MARTA BONATO¹, MARTINA BENINI¹,², SAM AERTS³, SILVIA GALLUCCI¹,², EMMA CHIARAMELLO¹, SERENA FIOCCHI¹, MARTA PARAZZINI¹, BARBARA MASINI¹, WOUT JOSEPH³, JOE WIART⁵, AND PAOLO RAVAZZANI¹

¹Istituto di Elettronica e di Ingegneria dell’Informazione e delle Telecomunicazioni (IEIIT), Consiglio Nazionale delle Ricerche, 20133 Milan, Italy
²Dipartimento di Elettronica, Informazione e Bioingegneria (DEIB), Politecnico di Milano, 20133 Milan, Italy
³Department of Information Technology, Ghent University/IMEC, 9020 Gent, Belgium
⁴Istituto di Elettronica e di Ingegneria dell’Informazione e delle Telecomunicazioni (IEIIT), Consiglio Nazionale delle Ricerche, 40136 Bologna, Italy
⁵Department of Communication and Electronic (COMELEC), Institut Mines-Telecom, 9120 Palaiseau, France

Corresponding author: Gabriella Tognola (e-mail: gabriella.tognola@ieiit.cnr.it).

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ABSTRACT Future vehicles will be increasingly connected to enable new applications and improve safety, traffic efficiency and comfort, through the use of several wireless access technologies, ranging from vehicle-to-everything (V2X) connectivity to automotive radar sensing and Internet of Things (IoT) technologies for intra-car wireless sensor networks. These technologies span the radiofrequency (RF) range, from a few hundred MHz as in intra-car network of sensors to hundreds of GHz as in automotive radars used for in-vehicle occupant detection and advanced driver assistance systems. Vehicle occupants and road users in the vicinity of the connected vehicle are thus daily immersed in a multi-source and multi-band electromagnetic field (EMF) generated by such technologies. This paper is the first comprehensive and specific survey about EMF exposure generated by the whole ensemble of connectivity technologies in cars. For each technology we describe the main characteristics, relevant standards, the application domain, and the typical deployment in modern cars. We then extensively characterize the EMF exposure scenarios resulting from such technologies by resuming and comparing the outcomes from past studies on the exposure in the car. Results from past studies suggested that in no case EMF exposure was above the safe limits for the general population. Finally, open challenges for a more realistic characterization of the EMF exposure scenario in the connected car are discussed.

INDEX TERMS Electromagnetic field exposure, Intelligent Transportation Systems, connected vehicle, V2X, advanced driver assistance systems, ADAS, IoT, intra-car wireless connectivity, 5G NR, radar.

NOMENCLATURE

| 3GPP | 3rd Generation Partnership Project |
| 5G-V2X | 5G Vehicle-to-Everything |
| ACC | Adaptive Cruise Control |
| ADAS | Advanced Driver-Assistance System |
| AMPS | Advanced Mobile Phone System |
| BLE | Bluetooth Low Energy |
| CDMA | Code Division Multiple Access |
| C-ITS | Cellular-ITS |
| C-V2X | Cellular-V2X |
| DSRC | Dedicated Short-Range Communication |
| ECU | Electronic Control Unit |
| E-field | Electric field |
| EIRP | Effective Isotropic Radiated Power |
| EMF | Electromagnetic Field |
| ERP | Effective Radiated Power |
| ETC | Electronic Toll Collection |
| FDD | Frequency-Division Duplex |
| FMCW | Frequency-Modulated Continuous Wave |
I. INTRODUCTION

The automotive field is experiencing a fast and pervasive technological innovation that is pushing towards the realization of the new concept of the connected car [1]. Modern and forthcoming scenarios of connected cars comprise (i) vehicles capable to communicate and exchange data with other vehicles, the infrastructure, and pedestrians to share real-time traffic information and alert signals (e.g., in case of car accidents, road interruptions, or obstacles), (ii) vehicles capable to sense outside and inside the cabin to provide driving assistance and to monitor the driver’s alertness and vital signs of car passengers, and (iii) vehicles that are equipped with wireless sensors and actuators capable to connect and exchange data with each other and the car’s electronic control unit (ECU) through an intra-vehicle network of Internet of Things (IoT).

The technologies used to operate such services generate an electromagnetic field (EMF) at different frequencies in the radiofrequency (RF) range, from a few hundred MHz, such as in intra-vehicle IoT communication deployed with ultra-high frequency (UHF) [2], to hundreds of GHz as in radars used for in-vehicle occupant detection [3].

Many of these technologies, such as radars used for driving assistance, parking aid, and collision warning, IoT for intra-vehicle sensor network, and wireless devices used for electronic toll collection (ETC), already have a widespread use and are nowadays present as standard equipment in all new cars, whereas other technologies will see widespread use in the coming years [4]. People in a car and in the car vicinity are thus daily exposed to EMF generated by devices in the car or mounted on the car body and by devices mounted on cars in the vicinity.

The present work gives for the first time a comprehensive survey of RF EMF exposure in the specific scenario of the connected car in the RF range, from 100 MHz to 200 GHz. In our survey, we grouped the technologies according to their purpose of use, namely in (i) technologies for vehicle-to-everything (V2X) communication, (ii) technologies for car sensing, and (iii) technologies for intra-vehicle wireless communication. For each group of technologies, we describe the EMF they generate and the impact they might have on EMF exposure of car passengers and people in the car vicinity, as derived from currently available studies. Open challenges and required RF EMF characterization in the connected car are identified and discussed.

II. TECHNOLOGIES FOR VEHICLE-TO-EVERYTHING COMMUNICATIONS

First, we review the technologies for V2X communications, i.e., the communications between the vehicle and other ‘entities’, such as vehicles (vehicle-to-vehicle, V2V), road infrastructure (vehicle-to-infrastructure, V2I), cellular network (vehicle-to-network, V2N), and pedestrians (vehicle-to-pedestrian, V2P). V2X will be the core communication technology in fully autonomous vehicles. It is for example used to communicate safety messages, such as do-not-pass warnings, blind curve/local hazard warnings, road works warnings, vulnerable road user (e.g., pedestrian, cyclist) alerts at a blind intersection, left-turn assist, and for management of vehicle platooning. V2X also comprises ETC, a particular case of vehicular communication between a vehicle and the infrastructure for the so-called electronic toll collection services.

The main characteristics of vehicle communication technologies, including a description of their application, the relevant standards, and the characteristic of the radiated field (i.e., the operating frequency band, bandwidth, and maximum transmit power) are listed in Table I.
TABLE I

| Application                                      | Technology          | Relevant standard                          | Frequency band (GHz) | Channel bandwidth (MHz) | Maximum transmitted power (dBm) |
|-------------------------------------------------|---------------------|--------------------------------------------|----------------------|-------------------------|-------------------------------|
| To communicate safety and non-safety messages    | IEEE 802.11p and   | IEEE std 802.11p [5]; ETSI EN 302 571     | 5.855 - 5.925        | 10                      | 33 (in EU and US for non-government services) |
| (e.g. warnings, infotraffic).                   | ITS-G5              | [6].                                        |                      |                         | 44.8 (in US for government services) |
|                                                 | LTE-V2X through PC5 or Uu interface | ETSI EN 303 613 [7]; 3GPP TR 36.885 [8]; | 5.855 - 5.925        | 10 or 20                | 23 (maximum power measured in a 1 ms frame) |
| To communicate safety and non-safety messages   | 5G-V2X              | 3GPP TR 38.886 (Rel.16) [10]; 3GPP TR 38.785 (Rel.17) [11]. |                      |                         | 23                            |
| (e.g. warnings, infotraffic). For advanced driving, depending on the automation level. |                     | ITS band: 5.855-5.925. FR1 band: 3.5 (TDD) or 2 (FDD). FR2 band: 28. |                      |                         |                               |
| Transport and Traffic Telematics systems for ETC| DSRC                | ETSI EN 300 674-2-2 [13].                  | 5.795-5.815          | 0.5                     | 14 or 21 (depending on OBU type and measured in a single side band) |

If not explicitly indicated, the maximum allowed transmitted power set by the standards is the EIRP calculated as \( A + G + 10 \log \left( \frac{1}{DC} \right) \), where \( A \) (dBm) is the measured power output of the device, DC is the duty cycle, and G is antenna assembly gain (dBi).

V2X is operated through two main wireless access technologies, both working in the Intelligent Transport Systems (ITS) band at 5.9 GHz, namely: WiFi for mobility based on the IEEE 802.11p standard used in the US [5] and denoted as ITS-G5 in the European Cooperative Intelligent Transport Systems (C-ITS) initiative [6] and cellular technology for V2X (C-V2X) [7]-[11].

The IEEE 802.11p protocol (Table I, first row) supports medium range (under 1 km), low latency (~2-10 ms) and high reliability communications also in adverse weather conditions (e.g., rain, fog, snow) [12]. Communication is fully distributed among vehicles and/or road side units (RSUs), without the intervention of any infrastructure, neither for resource allocation. Communication is operated in the ITS 5.9 GHz band with a channel bandwidth of 10 MHz, the maximum power that can be transmitted by the device’s antenna, as set by the standards, is 33 dBm both in EU and in the US, with 44.8 dBm also allowed in the US for government services.

C-V2X indicates an ensemble of technologies standardized by the 3rd Generation Partnership Project (3GPP) and includes V2X operated through both the Long-Term Evolution (LTE-V2X) [7]-[9] and 5G communication protocol (5G-V2X) [10], [11] and can operate via the infrastructure by using the Uu interface, i.e., the logical interface between the user equipment and the base station (e.g., to handle V2N use cases) or over the PC5 interface, enabling direct communications (also called sidelink communication) between vehicles (i.e., V2V) or between vehicles and other road users (i.e., V2P). In V2N, vehicle connectivity is obtained through the conventional cellular network to enable cloud services, such as infotainment and latency-tolerant road safety messages (e.g., information on longer-range road hazards and traffic conditions).

As far as LTE-V2X is concerned (Table I, second row), it supports both 10 MHz and 20 MHz channels, with a maximum transmitted power of 23 dBm. LTE-V2X can operate following two resource allocation schemes, called mode 3 and mode 4 for V2X sidelink communications, i.e., for direct communication through PC5 interface. In both modes the communication between vehicles or road actors is direct, but in mode 3, the cellular infrastructure manages the resource allocation and it works just in coverage, whereas in mode 4 vehicles autonomously select, manage and configure the communication, that can, thus, works also out of coverage.

As anticipated above, C-V2X can be operated also through the 5G NR (New Radio) communication protocol (Table I, third row). The use of 5G NR is required to enhance V2X services for future autonomous driving, which require ultra-reliable low-latency communications with high data rate and spectral efficiency. To satisfy the larger bandwidth needs of forthcoming advanced V2X use cases (e.g., in autonomous driving), 5G-V2X has been designed to operate not only in the ITS 5.9 GHz band (like in V2X operated through the LTE protocol) but also in the frequency range 1 (FR1, 410 MHz - 7.125 GHz) and the mmWaves frequency range 2 (FR2, 24.25-52.6 GHz).
Similarly to LTE-V2X, also 5G-V2X defines two new modes (modes 1 and mode 2) for the selection of sub-channels in 5G-V2X sidelink communications. These two modes are the counterparts to modes 3 and 4, however, LTE-V2X only supports broadcast sidelink communications while 5G-V2X supports broadcast, groupcast, and unicast sidelink communications.

Specifically, as reported in 3GPP Release 16 [10], 5G-V2X sidelink can be realized through the PC5 interface in the ITS 5.9 GHz band, in the 3.5 GHz (for time division duplex (TDD) devices) or 2 GHz (for frequency-division duplex (FDD) devices) bands for operation at FR1, and in the 28 GHz band for operation at FR2. Although 5G-V2X sidelink supports both FR1 and FR2, no specific optimization has been deployed for FR2 yet and most of the sidelink design refers to FR1. Indeed, we expect the sidelink design to be reengineered when considering the mmWave spectrum of FR2, due to its peculiarities. The channel bandwidth is 20 MHz for 5G-V2X operated at 5.9 GHz and can be as high as 100 or 400 MHz when the service is operated in FR1 and FR2, respectively. Like in LTE-V2X, the maximum transmitted power of the device is limited to 23 dBm.

Finally, ETC (Table I, last row) is a short-range radiocommunication technology between a roadside infrastructure and a vehicle or a mobile platform [13]. In addition to electronic toll collection per se, applications of ETC technology include parking payment, gas (fuel) payment, in-vehicle signing, traffic information, management of public transportation and commercial vehicles, fleet management, weather information, electronic commerce, probe data collection, highway-rail intersection warning, tractor-to-trailer data transfer, other content services, border crossing, and electronic clearance of freight. ETC is operated in the 5.795-5.815 GHz band, with a 0.5 MHz channel bandwidth; the maximum transmitted power of an ETC on-board unit (OBU) ranges from 14 to 21 dBm.

III. TECHNOLOGIES FOR CAR SENSING

Second, we review technologies used by automotive radars mounted on the car body or in the cabin. Radars mounted on the car body are used in advanced driver-assistance system (ADAS) applications to detect the presence of objects in the vicinity of the vehicle. Recently, radars are being used also inside the vehicle for vehicle occupant detection (VOD) applications, which aim to detect the presence of people inside the car and warn the driver of passengers left in the rear seats when the driver exits the car.

The main characteristics of car sensing technologies, including a description of their application, the relevant standards, and the characteristic of the radiated field (i.e., the operating frequency band, bandwidth, and maximum transmit power) are reported in Table II.

In ADAS, radars are mounted on the car body to sense the surroundings of the car and acquire information, such as the distance, velocity, direction, and angular position of objects that are in the radars’ range. This information is processed by the central processing unit or field-programmable gate array of the car to provide vehicle control corrections, collision warnings, and to prevent vehicle from accelerating into the front of vehicles or pedestrians ahead. ADAS is the core technology of the forthcoming fully autonomous vehicle. Depending on the specific application, ADAS is deployed through radars with a range from 1 to 250 m. ADAS radars are operated in the 24, 77, and 79 GHz band and can use pulse Doppler or frequency-modulated continuous wave (FMCW) technology [14]-[17]. The limit for the transmit power is typically around 20 dBm; however, depending on the type of technology, it can be as high as 50 dBm.

**TABLE II**

| Application | Technology | Relevant standard | Frequency band (GHz) | Bandwidth (GHz) | Limit of mean transmitted power (dBm) |
|-------------|------------|--------------------|----------------------|-----------------|--------------------------------------|
| ADAS a      | SRR 24 GHz NB | ETSI EN 300 440-1 [14] | 24.05-24.25          | 0.2             | 20                                   |
| ADAS a      | SRR 24 GHz UWB b | ETSI EN 302 288-1 [15] | 21.65-26.65          | 5               | 20 (measured in the 24.05-24.25 GHz band) |
| ADAS c      | LRR 77 GHz | ETSI EN 301 091-1 [16] | 76-77                | 1               | 23.5 (for pulsed radar); 50 (for other than pulsed radar) |
| ADAS d      | SRR 79 GHz | ETSI EN 302 264-1 [17] | 77-81                | 4               | 55 d                                 |
| VOD         | SRR        | -                  | 60-64 [19]-[26]; 76-81 [19]-[20]; 140 [3] | 4-7 (for 60 and 76 GHz radars); 13 (for 140 GHz radar) | 10-12                                |

The mean transmitted power reported in the table is the EIRP measured during an interval of time sufficiently long compared with the lowest frequency encountered in the modulation envelope of the signal transmitted by the device under test.

aTypical use cases include: blind spot detection, lane-change assist, front/rear cross traffic alert. bUWB band is valid from Jul 2013 to 1st Jan 2018 and subsequently extended by 4 years; after 1st Jan 2022, UWB band will be phased out. cTypical use cases include: ACC, emergency braking. dPeak EIRP power in a 50 MHz band.
TABLE III
CHARACTERISTICS OF TECHNOLOGIES FOR INTRA-VEHICLE WIRELESS COMMUNICATION

| Application                                                                 | Technology | Relevant standard                                                                 | Frequency band (MHz) | Channel bandwidth | Radiated emission limits for transmitter |
|----------------------------------------------------------------------------|------------|-----------------------------------------------------------------------------------|----------------------|-------------------|------------------------------------------|
| Smartphone pairing to the infotainment central unit of the car; multimedia in-cabin transmission; smart car access/start (incl. RKE, PaaK, PEPS); vehicle diagnostics (including TPMS); in-vehicle control settings. | BLE        | IEEE 802.15.1 [37]; ETSI EN 300 328 [38]; EN 300 440 [39]; EN 301 489-17 [40]; Bluetooth Core Specification [41]. | 2400-2483.5          | 2 MHz             | 20 dBm                                   |
| TPMS and RKE.                                                               | UHF short range | ETSI TR 102 649-2 [42]; EN 300 220-1 [43] and EN 300 220-2 [44]; ERC Recommendation 70-03 [45]; 47 CFR-Part 15 [46]. | Europe: 434, 868. US: 315, 434. Europe: ~200 kHz. US: 785.5 kHz at 315 MHz, 1.085 MHz at 434 MHz. Europe: 10 mW ERP at 434 MHz; 25 mW ERP at 868 MHz. US: 200 µV/m at a distance of 3 m. | ≥500 MHz or ≥20% the carrier frequency. |
| Smart car access (RKE); gesture recognition (e.g., to open car tailgate); recognition of child seats location and deactivation of corresponding airbag; automated trailer attach (clever trailer coupling). | UWB communication | 47 CFR-Part 15-Subpart F [47]; ETSI EN 302 065-3 [48]; IEEE 802.15.4z [49]. | Europe: 3100-4800 and 6000-9000; US: 3100-10600. | For narrowband NFC: 200 kHz. For wideband NFC: 14 MHz. | For narrowband NFC: 60 dBµA/m. For wideband NFC: 42 dBµA/m. |
| Smart car access/start (incl. PEPS, key less entry); Bluetooth/WiFi pairing with the car infotainment central unit. | NFC        | ISO/IEC 18000-3 [50]; ETSI EN 300 330 [51]; ERC Recommendation 70-03 [45]. | 13.56 | For narrowband NFC: 200 kHz. For wideband NFC: 14 MHz. | For narrowband NFC: 60 dBµA/m. For wideband NFC: 42 dBµA/m. |

ERP (effective radiated power): it is the power radiated in the direction of the maximum radiated power.

*Specifically indicated for automotive applications [42]. †H-field strength limit at a distance of 10 m.

Recently, automotive radars are being used also in VOD applications (see, e.g., [3], [18]-[26]) to detect how many passengers are in the car and which seats are occupied by passengers. Most VOD applications are able to recognize also the type of passenger in the car, distinguishing adults, little children, or even animals, and can record passenger breathing movements, generating warnings when these movements are different from what is expected from a healthy subject.

Although radars for VOD applications are already available on the market (see e.g., [19]-[26] in last row of Table II), their use is not yet formally standardized. This lack of standards / regulations specific to the use of radars inside a vehicle means that there is not yet a consensus among the manufacturers on the band at which the service is operated nor on the maximum transmitted power. From the review we made of the systems on the market, it appears that VOD radars are typically operated in the 60 GHz [19]-[26], 77 GHz [19], [20] and 140 GHz band [3]; usually, they are operated at significantly lower transmission power than in ADAS application, typically at 12 dBm.

IV. TECHNOLOGIES FOR WIRELESS INTRA-VEHICLE COMMUNICATION

Finally, in this group we review the technologies for wireless connectivity within the car and their typical applications, as listed in Table III.

Current cars are typically equipped with around 60-100 different on-board sensors to monitor the health of vehicle parts and to measure and control the vehicle’s asset and performance. The number of on-board sensors is expected to grow in the forthcoming years due to the increasing demand of more efficient and sustainable cars, supporting a higher degree of automation. Traditionally, on-board sensors have been connected to each other and the car ECU exclusively through cables; today, wire-only connection is no more sustainable as the cables needed to connect such a great number of sensors would increase the car weight and costs and diminish the fuel efficiency.

Wireless technology is frequently used in modern cars as a viable solution to replace (whenever possible) the sensors’ cables, as for example to replace with a wireless link the cables between the car windows, the mirrors, and the ECUs and to allow monitoring moving and difficult to access parts that can not be reached through a wired link, such as the tires.

Typical applications of intra-vehicle wireless connectivity are vehicle diagnostics, smart car access, in-vehicle control and personalization, infotainment, and in-cabin multimedia transmission [27]-[36]. As to vehicle diagnostics, wireless technology is used for example to: measure the temperature of the brake discs through wireless sensors mounted directly on the wheels of the car; measure in tire pressure monitoring
system (TPMS) applications the tire’s air pressure and temperature through a wireless sensor mounted on the tire valve; measure the level and flow of the fuel, the strain and vibration of the chassis, the torque of drive train, the engine’s valves displacement, the vehicle orientation and dynamics, the acceleration and displacement of the suspension system; in case of an accident, to measure the severity and the location of the impact on the vehicle.

In addition to vehicle diagnostics, wireless intra-vehicle connectivity is used for in-vehicle control and personalization such as in passive entry passive start (PEPS) modules that enable to unlocking the car and starting the engine with a smartphone, key fob or a smart card holding a digital key and for in-vehicle control services that allow the car to automatically recognize the driver’s smartphone and activate interior and/or exterior lighting, adjust seating, ventilation and air conditioning settings.

Finally, a common use of intra-vehicle wireless connectivity is for multimedia transmission within the vehicle cabin (e.g., for displaying multimedia contents to the screens of the rear passengers) and for pairing the smartphone to the car’s infotainment central unit to access to navigation, music and phone apps through the car dashboard while driving.

The main characteristics of intra-car wireless communication technologies, including a description of their application, the relevant standards, and the characteristic of the radiated field (i.e., the operating frequency band, bandwidth, and maximum transmitted power) are listed in Table III. As reported in Table III, intra-car wireless communication is deployed on current vehicles through Bluetooth low energy (BLE), UHF short range communication, ultra-wide band (UWB) communication, and near-field communication (NFC).

BLE is a short range communication developed by the Bluetooth Special Interest Group and is characterized by ultra-low power consumption and transmission efficiency [37]-[41]. BLE is operated in the 2.4 GHz industrial, scientific and medical (ISM) band and supports up to 100 mW (+20 dBm) transmitted power.

UHF short range communication [42]-[46] is used in automotive connectivity for enabling TPMS and remote keyless entry (RKE) services; it is operated in the 315, 434, and 868 MHz bands and supports up to 10 or 25 mW transmitted power, depending on Regional regulations and operating band.

UWB is a short range communication that uses a relatively large bandwidth of 500 MHz or more and/or a bandwidth that is at least 20% the carrier frequency [47]-[49]. It is operated in the unlicensed 3.1-10.6 GHz band and supports a mean power spectral density of -41.3 dBm/MHz.

Finally, NFC is a short range contact-less technology [45], [50], [51]; by using magnetic induction, it enables the exchange of data and transfer of power between devices by bringing them into close proximity to a distance of a few centimeters. NFC is operated at 13.56 MHz and supports a magnetic field (H-field) limit of 42 dBµA/m or 60 dBµA/m, depending on the bandwidth of the device.

V. EMF EXPOSURE ASSESSMENT IN THE CONNECTED VEHICLE

In the current Section V, we describe the main evidences from currently available literature on the assessment of the exposure field and the dose absorbed by passengers of cars equipped with the technologies previously described.

A. THE EXPOSURE SCENARIO

Due to its partially closed structure, the car is a peculiar exposure scenario, which can generate standing waves and a loss of the power transmitted in the cabin from a source external to the vehicle (e.g., an antenna mounted on the car roof).

As to standing waves, Hirata and Iida [52] found that the electric field (E-field) induced inside the car by an external plane wave at 10 MHz-1 GHz was enhanced at ~120 MHz, due to the standing waves generated inside the vehicle cabin. Standing waves were suppressed in the 100-200 MHz range when a human body was present inside the vehicle, due to the power absorbed by the car occupant [52]. Also, in the frequency region of standing wave suppression (i.e., at 100-200 MHz), the dose of EMF absorbed by the car occupant at the whole-body level was lower inside the car than in free space [53]. Vice versa, at frequencies outside the 100-200 MHz range, the presence of a car occupant had only a marginal effect on the suppression of the standing waves [52]. The frequency region at which standing waves were suppressed depends on the dimension of the vehicle cabin and the number and size of car windows. The presence of passengers in the car generated a similar suppression effect of also the exposure field: as observed in [54], the average in-vehicle E-field was lower in the presence of passengers than in an empty car.

The car body also causes a loss in the penetration inside the car of fields generated by antennas mounted on the roof of the car or mounted on the road infrastructure. The amount of penetration loss depends on the size of the car and the number and size of the car windows. As observed in [55], RF penetration loss due to the car body could be as high as 3.2-23.8 dB at 600-2400 MHz. As a consequence, it is expected that EMF exposure generated by sources external to the vehicle would be lower inside the vehicle cabin than outside.

B. THE LIMITS FOR EXPOSURE IN THE RF RANGE 100 KHZ - 300 GHZ

Absorption of RF EMFs can generate a temperature rise in the body. The exposure limits recommended by the International Commission on Non-Ionizing Radiation Protection (ICNIRP) [56] and IEEE [57] were set to keep the local and core body temperature rise to a safe level. Namely, compliance with these latter limits would provide a protection against potential adverse health effects that are observed when the core body
temperature increases over 1 °C and local body temperature increases more than 5 °C for Type-1 tissues (all tissues in the upper arm, forearm, hand, thigh, leg, foot, pinna and the cornea, anterior chamber and iris of the eye, epidermal, dermal, fat, muscle, and bone tissue) and 2 °C for Type-2 tissues (all tissues in the head, eye, abdomen, back, thorax, and pelvis, excluding those defined as Type-1 tissue) [56].

As to core body temperature rise, the basic restrictions for exposure in the RF range 100 kHz - 300 GHz [56], [57] are set in terms of the specific energy absorption rate (SAR) at the whole body, that is the power absorbed per unit mass of the entire body. For the general public, the whole body SAR exposure limit is equal to 0.08 W/kg, averaged over 30 minutes of exposure [56], [57]. As to local body temperature rise, the basic restrictions for exposure fields within the 100 kHz - 6 GHz range are set in terms of the local SAR averaged over 10 g of mass, with a limit of 2 W/kg and 4 W/kg for local exposure at the head/torso and the limbs, averaged over 6 minutes [56], [57]. For frequencies within the >6 GHz - 300 GHz range, as the RF energy is deposited mainly at superficial tissues and not in deeper tissues as for lower frequencies, the basic restrictions are set in terms of the local absorbed power density ($S_{ab}$), that is the density of the power absorbed over a square 4-cm$^2$ surface area of the body; the limit is set to 20 W/m$^2$, averaged over 6 minutes [56], [57].

In case in which it is not feasible to measure the power absorbed in the body, it is possible to assess compliance with the so-called reference levels that are based on exposure quantities that shall be measured outside the body, that is the incident E-field and H-field strength and the incident power density. For exposure in the far-field zone at frequencies ≤2 GHz, compliance shall be assessed with either the E-field or H-field or the incident power density reference levels; these latter reference levels depend on the frequency of the emitting source [56], [57]. For frequencies >2 GHz, like in automotive radars and V2X communication, compliance shall be assessed with the reference level based on the incident power density only, which is equal to 10 W/m$^2$ averaged over 30 minutes, at any frequency >2 GHz [56], [57].

C. METHODS FOR RF EXPOSURE ASSESSMENT

Table IV and Table V list an overview of EMF exposure assessment in the car at frequencies used in V2X communication, intra-car communication, and generic wireless communication services used in the car (Table IV) and in the 24-100 GHz band of automotive radars (Table V).

For each study listed in Table IV and Table V, we report all the relevant details, namely the frequency and the power radiated by the investigated RF source, the method used to assess the exposure inside the car, the use-case (i.e., exposure scenario) addressed, the estimated / measured exposure quantity, and the main outcomes. For the sake of clarity, we preferred to put all the analytical details of the studies in Table IV and Table V, while we resumed in the following paragraphs only the main outcomes by grouping the studies in clusters with similar research aims and setups.

As described in Table IV and Table V, in-cabin field exposure assessment was typically performed through experimental measurements and numerical simulations. In experimental studies (see [62], [64]-[69] in Table IV and [80], [81] in Table V), the aim was to measure inside the cabin of a real vehicle the field exposure generated by one or more RF device placed either outside (e.g., on the car roof) or inside the car (e.g., at the front dashboard). Measurements were done in the empty car (i.e., with no car occupants inside) at typically the driver and passengers’ seats to assess compliance with exposure limits in the most critical positions, that is the positions occupied by car passengers. All experimental studies ([62], [65]-[69], [80], [81]) but [64], measured the E-field: as such, for these former studies, the compliance with exposure limits can be assessed by comparing the measured E-field against the reference E-field level in [56] and [57]. Instead, the latter study [64] measured the SAR inside an anatomically-realistic adult human phantom that consisted of a fiberglass shell filled with a material of the same dielectric properties of the human muscle tissue. The phantom was seated inside a real car; SAR was measured by placing the measuring probe in the phantom’s head. For this latter study, the compliance with exposure limits can be assessed by comparing the measured SAR against the basic SAR restrictions in [56] and [57].

In numerical simulation studies (see [58]-[61], [63], [70]-[79] in Table IV and [58], [82]-[85] in Table V) the aim was to estimate the exposure field using numerical methods capable to calculate electromagnetic quantities, such as the E-field and H-field, as generated by a simulated source in a simulated exposure scenario.

The numerical simulation approach can be purely analytical or can use computational electromagnetic methods. Any analytical approach relies on a strong simplification of the exposure scenario and does not allow taking into account the potential effects on the exposure field of the real 3D geometrical shape neither of the car nor the emitting antenna. For example, in [58] an analytical approach – the power balance method [87] – is applied to estimate the average E-field strength inside a vehicle cabin in the 0.9-5.8 GHz frequency range. The application of the power balance method relies on the assumption that at frequencies above ~1 GHz, the vehicle cabin can be approximated as an electrically large cavity where the average internal E-field strength is a function of basically only the windows’ size and glazing materials [58]. The output of an analytical approach is typically the E-field strength and the power density; compliance with exposure limits shall thus be assessed using reference levels in [56] and [57]. Being based on strong approximations, the analytic approach is useful to gain a first insight on the exposure field when it is not possible to implement more computational demanding methods capable to model and take into account the 3D geometry of the exposure scenario (i.e., the car, the emitting antennas, and the car’s occupant(s)).
In addition to the analytical approach described above, numerical simulation of the exposure field can be done also using computational electromagnetic approaches capable to solve Maxwell’s equations directly, as the Finite-Difference Time-Domain (FDTD) method [88]. Examples of application of computational electromagnetics for field exposure assessment in the car are in [59]-[61], [63], [70]-[79] in Table IV and [82]-[85] in Table V. In computational electromagnetics, the exposure scenario is modelled using 3D geometries; the scenario is then discretized in terms of grids and Maxwell's equations are solved at each point in the grid. The scenario typically includes the 3D geometric model of the emitting antenna(s) (that could be as schematic as a simple monopole/dipole antenna or more complex as a 3D model of the entire emitting device, case included), the 3D geometric model of the car (simplified or a realistic CAD model) and the 3D human phantom (simplified as a spheroid or detailed and anatomically realistic, including all organs and body tissues). Computational electromagnetic approaches allow the computation of electromagnetic quantities both in the space around the human phantom and, most important, inside the phantom (and in every tissue/organ), being thus a consolidated and robust methodology to assess the SAR and the $S_{th}$ in the body and its tissues. The drawback of computational electromagnetic approaches is that they are computationally demanding, especially when the simulated exposure scenario occupies large volumes in space, like in automotive scenarios.

**D. IN-CABIN FIELD EXPOSURE ASSESSMENT TO FREQUENCIES USED IN V2X, INTRA-CAR AND GENERIC IN-CAR WIRELESS COMMUNICATION**

Table IV gives an overview of EMF assessment in cars in the 100 MHz – 10 GHz range that covers V2X communication, intra-car communication, and generic wireless communication services used in the car, such as mobile communication, WiFi, and Bluetooth. We grouped the studies in Table IV in three clusters based on the scenario they addressed, that is: specific V2X exposure scenarios (Section D.1) and generic in-car connectivity exposure scenarios generated either by antennas external to the car (Section D.2) or antennas placed inside the car (Section D.3).

**TABLE IV**

| Study name                        | Frequency and power of analyzed EMF source | Study type and setup | EMF source position | Quantity measured/estimated & main study outcomes |
|-----------------------------------|--------------------------------------------|----------------------|---------------------|--------------------------------------------------|
| Ruddle [58]                       | 5.8 GHz at 33 dBm (2 W) EIRP              | Analytical simplified model of in-vehicle E-field strength. | External: DSRC device (toll beacon) at 5 m from the car. | Power density coupled inside the vehicle cabin: 0.005 W/m². |
| Tognola et al. [59], [60]         | ITHS 5.9 GHz at 33 dBm EIRP              | Numerical simulation using a realistic 3D model of a car and an adult human phantom as a car passenger (at the driver position). | External: four V2V antennas mounted on the roof of the car. | Whole body SAR and peak SAR$_{th}$: the maximum value of SAR was obtained with four antennas and was equal to 0.008 W/kg for the whole body, 1.58 W/kg at the head/torso, and 0.76 W/kg at the limbs. |
| Baramili et al. [61]              | LTE: (690-960 MHz), (1710-2170 MHz), (2400-2700 MHz). 5G: (600-960 MHz), (3300-5000 MHz) * | Numerical simulation using a 3D model of a car with a realistic human phantom at the driver position. | External: one antenna integrated in the glass of either the front or rear window. | E-field inside the vehicle cabin at the driver position: for all bands and the two antenna positions, the maximum was below 24 V/m. |
| Tarusawa et al. [62]              | 900 MHz at 1 W input power               | Experimental measurement of E-field inside the cabin of a real car. | External: one antenna mounted either on the car roof or the trunk lid or the rear window. | E-field inside the vehicle cabin: the maximum was 8 V/m, 30 V/m, and 32 V/m as generated by the trunk-lid, the rear window, and the roof antenna respectively. |
| Ruddle et al. [63]                | 400 and 900 MHz at 1 W                   | Numerical simulation using a 3D model of a car and 4 human phantoms as car passengers. | External: one antenna mounted outside on the car’s roof. | Whole-body and local SAR: the highest SAR was obtained for the whole-body at 400 MHz and was below 0.6% of the basic restrictions. |
| McCoy et al. [64]                 | VHF (146 MHz) at 100 W; UHF (460 MHz) at 102 W. | Experimental measurement of SAR in an adult human phantom seated inside the car. | External: antenna mounted on the trunk of the car. | Peak SAR$_{th}$: the highest value was around 2.3 mW/kg for both frequencies and was observed in the head region. |
| Authors          | Frequency Range | Method Description                                                                 | Measurement Details                                                                 | Result                                                                 |
|------------------|-----------------|-------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------|----------------------------------------------------------------------|
| Anzaldi et al.   | GSM 1800 MHz    | Experimental part: measurement of E-field inside the vehicle cabin                  | Internal: one antenna mounted at the center of the cabin’s roof                     | E-field inside the cabin: the maximum was 7 V/m (measured experimentally) and 7.4 V/m (estimated from numerical simulations). |
| Rodrigues et al. | 2.047 GHz at 500 mW input power. | Experimental measurement of E-field inside two real cars of different size (compact and sedan models). | Internal: four antennas mounted at the front and rear passenger seats, at an height of an handheld used phone. | E-field inside the vehicle cabin: the maximum value estimated at the driver, front passenger and rear seats was achieved when all antennas were switched on and was within 18 V/m. |
| Buckus et al.    | GSM 900 and 1800 MHz band at 0.25–2 W maximum output power level. | Experimental measurement of E-field in a real car driving in the 200 m beam (urban area) and 1000 m beam (rural area) of the BS. | Internal: various GSM phones with different power levels, used inside the car during an outgoing call. | E-field inside the vehicle cabin: at 20 cm from the phone, the maximum value was 7 V/m in urban area, obtained with a GSM 1800 (1 W) and 10 V/m in rural area, obtained with a GSM 900 (2 W) phone. |
| Psenakova et al. | Bluetooth, 2400 MHz; GSM 800 MHz; UMTS 2100 MHz | Experimental measurement of E-field during a phone call inside a real car equipped with built-in Bluetooth connectivity. | Internal: a GSM/UMTS phone placed on the dashboard compartment of a car equipped with a built-in Bluetooth antenna. | E-field inside the vehicle cabin, measured at the chest level of the driver: the maximum was around 48.48 mV/m at 800 MHz, 72.54 mV/m at 2100 MHz, and 218.1 mV/m at 2400 MHz. |
| Aguirre et al.   | ZigBee (2.4 GHz) at 63 mW; GSM (900 and 1800 MHz); UMTS (2100 MHz). | Experimental measurements of E-field inside the cabin of a real vehicle in an urban area. | Internal: a ZigBee antenna and a multi-band GSM/UMTS placed on the front dashboard. | E-field inside the car: the maximum value generated by the ZigBee antenna was 2 V/m; for GSM and UMTS, the maximum was below 1.5 V/m. |
| Ruddle          | 0.9/1.8/2.1/2.4 GHz at 1 W radiated power | Analytical estimation through power balance methods of in-vehicle E-field strength. | Internal: simulated in-vehicle transmitters equivalent to mobile phones (at 0.9/1.8/2.1 GHz) and personal devices (2.4 GHz WiFi and Bluetooth). | E-field inside the vehicle cabin: the average value was below 25 V/m RMS for 1 W of radiated power, at all frequencies. When devices were operated at their maximum EIRP, the highest value of the E-field was 31.8 V/m and was generated by the 0.9 GHz device at 2 W EIRP. |
| Low and Ruddle   | 900, 1800, 2400 MHz at 1 W radiated power | Numerical simulation with a realistic 3D model of a car to estimate E-field inside the car cabin. | Internal: one antenna placed inside the cabin either at the top of the windshield or on a storage box located between the two front seats. | E-field inside the car: the highest average value (19.03 V/m) was at 900 MHz. At 1800 and 2400 MHz the average E-field was slightly lower. |
| Toropainen      | AMPS (800 MHz), GSM (900, 1800 MHz), and CDMA (2000 MHz). | Numerical simulation to estimate the equivalent power density and whole-body SAR inside a resonant metal cavity with dimensions of a real car. | Internal: mobile phones placed inside the cavity. | Basic restriction limits are exceeded only when using 30-160 mobile phones operated at the same time at their maximum power in the car, i.e., with a number of devices much higher than the number of possible users in the car. |
| Lee et al.       | 1-3 GHz; the antenna input power was adjusted to generate an | Numerical simulation using a 3D model of a car and a homogeneous spheroid mimicking a | Internal: one antenna with horizontal or vertical polarization, mounted at different | Whole-body SAR: the highest value (14 µW/kg) was obtained at 1 GHz with an horizontally polarized antenna mounted at the middle of the car dashboard. |
| Authors              | Frequency Range | Power Level | Description                                                                 | Internal SAR Evaluation                                                                                                                   | External SAR Evaluation                                                                 |
|---------------------|-----------------|-------------|-------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------|
| Anzaldi et al. [73] | 835 MHz at 0.58 W radiated power. | Numerical simulation using a 3D model of the car, a human phantom seated inside the car, and a phone. | Internal: phone in hands-free use (placed to the right of the steering wheel) and hand-held use (phone held by the front passenger, close to the right side of the head). | SAR evaluated over three planes: at the heart, thighs, and eye level.¹ In hands-free use, the maximum SAR of 56 mW/kg was at heart plane level, in the right arm; in hand-held use, the maximum SAR of 2 W/kg was at the eye plane level, at the right side and 15 mm toward the interior of the head. |                                                                                           |
| Chan et al. [74]    | 900 MHz at 2 W radiated power. | Numerical simulation with a simplified 3D model of a car and simplified human phantoms as car passengers (4 in total). | Internal: a simplified 3D model of the emitting device (a phone) is placed at ear level near the head of the user (single user). | The highest SAR (0.472 W/kg) was observed with 4 people (1 user + 3 passengers) in the car. |                                                                                           |
| Leung et al. [75]; Diao et al. [76] | 900 MHz at 2 W; 1800 MHz at 1 W; 2400 MHz at 0.1 W. | Numerical simulation with a simplified 3D model of a car and simplified human phantoms as car passengers (5 in total). | Internal: a simplified 3D model of the emitting device (a phone) is placed at ear level near the head of the user(s). One- and two-user conditions are considered. | Single-user condition: the highest SAR was 3.02 W/kg at 900 MHz, 1.88 W/kg at 1800 MHz, 0.19 W/kg at 2400 MHz. Two-user condition: the highest SAR was (3.77 W/kg) was observed using two phones operated at 900 MHz. Other combinations of phone/frequencies resulted in lower SAR values. |                                                                                           |
| Ruddle et al. [63]  | 400, 900, 1800, and 2400 MHz at 1 W. | Numerical simulation using a 3D model of a car and 4 human phantoms as car passengers. | Internal: one antenna mounted inside the vehicle cabin. | Whole-body and local SAR: the highest SAR was at 400 and 900 MHz (equal to 9.9% and 8.6% of basic restrictions, respectively); SAR at 1800 and 2400 MHz was lower (4.6% and 3.6% of basic restrictions, respectively). The head and trunk were the regions with the highest SAR at 900, 1800, and 2400 MHz; at 400 MHz, the highest SAR was at the whole-body level. |                                                                                           |
| Harris et al. [77]  | UMTS (2.1 GHz) at 125-250 mW radiated power; WiMax (2.5 GHz) at 200 mW radiated power; Bluetooth (2.45 GHz) at 2 mW. | Numerical simulation using a 3D model of a car and human phantoms of adult and child passengers in the car. | Internal: the emitting devices were placed inside the vehicle cabin at the driver and passenger seats. Single-user (i.e., only one device operated at a time) and two-user (two devices operated at the same time) scenarios were evaluated. | Whole-body SAR: the highest value was obtained in the two-user scenarios with two UMTS devices and was equal 2.13 mW/kg. Local SAR_{head}: the highest value in the head/trunk was obtained with UMTS and was equal to 25.3 mW/kg; in the limbs, the highest value was obtained with the WiMax device and was equal to 392.6 mW/kg. The contribution of the Bluetooth device to the SAR is not significant. In all conditions, the highest SAR was observed in the configuration with 1 adult + 3 children as car passengers. |                                                                                           |
| Jeladze et al. [78] | 450, 900, and 1800 MHz bands at 1 W. | Numerical simulation using a 3D model of a car and a human phantom at the driver position. | Internal: a mobile phone antenna at 2.5 cm from the phantom head. | Point SAR: the maximum was 96 W/kg at 450 MHz, 296 W/kg at 900 MHz, and 127 W/kg at 1800 MHz. |                                                                                           |
| Aminzadeh et al. [79] | Bluetooth 2400-2450 MHz at 2.5 mW. | Numerical simulation: 3D model of a car with a human phantom inside, wearing a mobile headset. For the human | Internal: one headset worn at the left ear of the passenger. | SAR_{head} and SAR_{body}: the maximum was observed at the ear level and was equal to 0.1153 W/kg for SAR_{head} and 0.0486 W/kg for SAR_{body}. |                                                                                           |
1) IN-VEHICLE EXPOSURE FROM SPECIFIC V2X COMMUNICATION

To the best of the authors’ knowledge, there are only a very few studies ([58], [59], [60]) on EMF exposure in specific V2X scenarios, whereas most of the past studies focused on in-vehicle exposure from generic wireless communication used in cars, such as mobile communication (e.g., Global System for Mobile Communications-GSM, Universal Mobile Telecommunications Service-UMTS, and LTE), Bluetooth and WiFi.

As to exposure assessment in V2X scenarios, a first attempt was done by Ruddle [58] (Table IV) that used a simplified analytical approach for evaluating the field coupled inside a car from an external ETC device (a toll beacon) at 5.8 GHz. The ETC device was simulated at the maximum allowable Effective Isotropic Radiated Power (EIRP), at 5 m from the car. Results evidenced that the power density coupled inside the vehicle was 0.005 W/m², that is well below the safety reference level of exposure of 10 W/m² for the general population [56], [57].

A more realistic and complex exposure scenario was addressed for the first time by Tognola et al. [59], [60] (Table IV) who assessed RF exposure in a realistic anatomical human phantom seated at the driver position inside a 3D model of a real city car equipped with V2V external antennas mounted on the roof. The dose absorbed by the driver at the typical V2V ITS 5.9 GHz band was quantified as the SAR. As observed in [59], [60], the dose was mainly absorbed at the most superficial tissues of the body - the skin - and in the head. In the worst-case scenario (that consisted of four antennas operated at the same time and at the maximum EIRP) the dose absorbed by the whole body (0.008 W/kg), at the head/torso (1.58 W/kg), and the limbs (0.76 W/kg) was well below the basic restriction limit for EMF exposure of the general population at 100 kHz-300 GHz, which is equal to 0.08 W/kg for the whole body, 2 W/kg in 10 g tissue for the head/torso, and 4 W/kg in 10 g tissue for the limbs [56], [57].

2) IN-VEHICLE EXPOSURE FROM GENERIC IN-CAR WIRELESS COMMUNICATION – EXTERNAL ANTENNAS

The remaining studies listed in Table IV investigated in-vehicle field exposure generated at the frequencies used in generic wireless communications by external (described in this current Section D.2) and internal antennas (Section D.3).

As to external antennas, studies [61]-[64] in Table IV addressed antennas mounted on the car body in the Very High Frequency-VHF (146 MHz), UHF (460 MHz), GSM (900 and 1800 MHz), 5G NR (600 and 3500 MHz), and WiFi (2400 MHz) bands. In all studies, in-cabin exposure field was found to be below the reference level of exposure of 27.7 V/m at 146 MHz, 29.5 V/m at 460 MHz, 41.25 V/m at 900 MHz, 58.3 V/m at 1800 MHz, 67.4 V/m at 2400 MHz, and 81.3 V/m at 3500 MHz as set in [56], [57]. Similarly, the dose absorbed by the passengers in the car was below the basic restrictions for the general public at all bands mentioned above. As a general remark, the highest exposure was observed at the whole body and in the head region [63], [64].

3) IN-VEHICLE EXPOSURE FROM GENERIC WIRELESS IN-CAR COMMUNICATION – INTERNAL ANTENNAS

Studies [58], [65]-[79] in Table IV addressed EMF exposure from antennas and devices operated inside the vehicle, such as mobile phones (GSM 900 and 1800 MHz and UMTS 2100 MHz) and Bluetooth, WiFi, and ZigBee devices.

Field exposure inside the vehicle cabin measured experimentally [65]-[69] or assessed with numerical simulations [58], [63], [70]-[79] was again below the reference level of exposure, at all tested frequencies. The dose absorbed by the passenger closer to the emitting device(s) slightly increased with the number of car occupants (see e.g., [74]) and the number of devices simultaneously used in the car (see e.g., [75], [76]). In any case, the dose of exposure was always below the basic restriction limits [56], [57].

E. IN-CAabin FIELD EXPOSURE ASSESSMENT TO FREQUENCIES USED IN AUTOMOTIVE RADAR APPLICATIONS

Table V summarizes the outcomes from studies on field exposure at radar frequencies, i.e., 24-100 GHz.

As a general remark, we did not find any study addressing realistic scenarios of automotive applications of radars. The best approximation of a realistic automotive radar scenario was in [80] and [81]. Study [80] assessed the exposure from automotive radars by applying a horn antenna to measure the increase of the superficial temperature of the human skin and porcine eye. The horn antenna was fed with a continuous wave at 1-10 mW/cm² power density at 77 GHz. The measured temperature rise was well below the safe limit of 2-5 °C even at an incident power density of 10 mW/cm² (~100 W/m²), which is ten times greater than the reference exposure limit [56], [57]. In [81], a 79 GHz automotive radar is analyzed to measure the power density emitted at 3-30 mm distance in the worst case scenario of 100% duty cycle and maximum output power. The study evidenced that the power density averaged over 1 cm² was well below the limits for exposure [56], [57].

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TABLE V
STUDIES ON EMF EXPOSURE ASSESSMENT INSIDE THE CAR – FREQUENCIES IN THE 24-100 GHz REGION

| Study name                  | Frequency and power of analyzed EMF source | Study type and setup | EMF source position | Quantity measured/estimated & main study outcomes |
|-----------------------------|--------------------------------------------|----------------------|---------------------|----------------------------------------------------|
| Gustrau and Bahr [80]        | 77 GHz continuous wave at 1 and 10 mW/cm², incident power density | Experimental measurement of superficial temperature increase in vivo (human skin) and in vitro (porcine eye) | Measurements are done in air with the emitting antenna close to the analyzed tissue. | Temperature rise: <0.1 °C and 0.7 ± 0.15 °C at 1 mW/cm² and 10 mW/cm² power density respectively. |
| Vermeeren et al. [81]       | 79 GHz at maximum output power (10 dBm) | Experimental measurement of the power density. | Measurements are done in air at a 3-30 mm distance above the antenna surface. | Spatial-averaged power density: the maximum value of 50 W/m³ averaged over 1 cm³ was observed at 3 mm distance from the antenna. |
| Ruddle [58]                 | 24/46.8/77 GHz ADAS radar.⁴     | Analytical estimation through power balance methods of in-vehicle E-field strength. | External: radar antenna simulated at 3 m from car. | Power density coupled inside the vehicle cabin: among all tested sources, the highest value of 0.76 W/m³ was obtained with the 77 GHz radar; the smallest value (0.0005 W/m³) was with the 24 GHz radar. |
| Vilagosh et al. [82]        | Pulsed excitation of 100 ps duration at 30, 60, 90 GHz.⁵ | Numerical simulation using a 3D realistic anatomical model of the car. The car is not modelled. | Plane wave in air directed towards the car model at different incident angles. | Temperature rise in 5 s: the highest value was found at 90 GHz in the tympanic membrane, with a temperature rise of 0.00645 °C. |
| Laakso et al. [83]          | Plane wave at 6-100 GHz of 1000 J/m², incident energy density and pulse duration of 0.1-10 s. | Numerical simulation using a 3D anatomical model of only the eye. The car is not modelled. | Plane wave in air directed towards the eye model. | Temperature rise: the highest temperature rise was ~0.5 °C (mean value over all the tissues and structures of the eye) at 100 GHz for pulse duration of 0.1 s. The temperature rise decreased with frequency and for longer pulse duration. |
| Simic et al. [84], [85]⁶    | UWB pulses at 22-29 GHz and 57-64 GHz. | Numerical simulation using 3D anatomical model of only the eye. The car is not modelled. | Plane wave in air directed towards the eye model. | Energy absorption: the energy is absorbed in the eye tissues in the same way for UWB pulses and CW excitation. At 22-29 GHz and 57-64 GHz the energy is mostly absorbed by the cornea. |

⁴The devices are operated at the maximum average power density allowed at a distance of 3 m, as established in [86], that is: 0.0009 W/m² for 24 GHz side/rear radar; 0.3 W/m² for 46.8 GHz side/rear radar; 0.6 W/m² for 46.8 GHz ACC radar; 0.88 W/m² for 77 GHz side/rear/ACC radar. ⁵The amplitude of the excitation signal was adjusted to the general public exposure recommendations of a maximum incident power density of 10 W/m² [56], [57]. ⁶The papers do not specify the output power of the tested antennas.

Another quite realistic scenario was addressed in [58] that analytically estimated the effect of the car body on the field coupled inside the vehicle cabin. In [58], it is observed that the power density coupled inside the vehicle from a radiating antenna at 24, 46.8 and 77 GHz at the maximum EIRP was 0.76 W/m² at a distance of 3 m from the antenna, that is well below the reference exposure limit of 10 W/m² [56], [57].

The remaining papers [82]-[85] in Table V addressed extremely simplified exposure scenarios to estimate the temperature rise in 3D numerical models of the ear and the eye in the range of frequencies used in automotive radars. The excitation source was a pulsed plane wave in the air at the ICNIRP maximum power density of 10 W/m² [56]. Results evidenced that the temperature rise was of the order of 0.5 °C, that is below the local exposure safe limit of 5 °C for Type-1 tissues and 2 °C for Type-2 tissues [56], [57].

VI. OPEN ISSUES
Despite the massive and pervasive use in modern vehicles and the resulting potential impact on the health of car occupants, we could find only a very few studies that addressed the specific scenario of EMF exposure in the connected car. The majority of past studies focused on the use of generic personal wireless communication technologies, such as mobile phones, Bluetooth and WiFi devices. Only a few studies ([58], [59], [60]) addressed technologies specific to car connectivity, such as V2V. As for car sensing, we found only studies addressing extremely simplified exposure scenarios. Finally, we could not find any study on the exposure generated by IoT sensors and actuators, specifically used in intra-vehicle wireless networks.

Research on EMF exposure in the connected car shall go deeper in the forthcoming years to address more realistic scenarios to consider aspects not yet investigated, such as:
1) The effect of the combined use of technologies operating at different frequency bands. As described in the current paper, a connected car is a kind of ‘ecosystem’ where a variety of different wireless technologies are used at the same time, e.g., ADAS radars, antennas for V2X connectivity, intra-car wireless connectivity and infotainment that are operated at different frequency bands. Thus, a realistic assessment of RF exposure in car passengers shall take into account the peculiarity of this multi-source and multi-frequency scenario. At the moment, current studies addressed only single-frequency scenarios. Instead, in situations of simultaneous exposure to fields at different frequency bands (like in the connected car), it is important to assess the compliance with exposure limits not only in each separate frequency band but also as a whole to account for possible additive effects of multiple exposure [56], [57]. As a matter of fact, recommendations in [56], [57] provide specific formulae to assess cumulative exposure by assuming worst-case conditions (i.e., pure additive effects) among the fields from multiple sources.

2) The effect of the number of devices simultaneously used in the car. Differently from use-cases that are already extensively addressed in the literature where the exposure scenario consists of a user and a single source of EMF, e.g. in the assessment of the dose absorbed by using a smartphone or a tablet, the typical exposure scenario in the car is intrinsically a multi-source one. V2X connectivity, for example, requires multiple antennas to be mounted on the car roof or embedded in the windscreen or the external mirrors; in intra-car wireless connectivity, multiple IoT sensors and actuators are placed on different parts of the car; similarly, a typical ADAS implementation requires multiple radars mounted on the car body, e.g., on the bumpers and at the sides of the vehicle. Even by considering the simplest scenario of a single technology (i.e., a single frequency band), the exposure field inside the car varies with the number of devices as it is influenced not only by pure additive effects but also by resonance and interference effects generated by the partially closed structure of the vehicle cabin [52]-[54].

3) The effect of the variability of the exposure scenario, e.g., the effect of the size and shape of the car, the age (children vs. adults and pregnant women) and size of passengers (height, weight, body composition), the position of the devices and passengers in the car (EMF exposure depends on the distance between the source of the field and the person). For example, as to the effect of age, it is well known that the dose of EMF absorbed by a person varies with the person’s age as a result not only of the different total body mass (adults are bigger and heavier than children and neonates) but also the different body composition (muscle and fat tissues have different dielectric properties and thus they absorb the field in a different way). As a matter of fact, previous studies (see, e.g., [89], [90]) observed that whole body and local SAR could have higher levels in children than adults, for identical exposure conditions. Because of the massive number of computationally demanding simulations that would be required, characterization of such variability is nearly unfeasible using deterministic dosimetry (as done by the studies in the current survey) and standard techniques of uncertainty propagation, such as Monte Carlo method [91]. Recently, advanced statistic approaches such as stochastic dosimetry and Machine Learning were applied to build computationally efficient surrogate models to assess EMF exposure in complex and uncertain scenarios [92]-[94]. It is thus recommended that future assessment of EMF exposure in the car would address uncertainty and variability of the exposure scenario with such innovative approaches.

4) Last but not least, exposure in the connected vehicle shall address the new forthcoming scenarios that will make use of innovative communication technologies such as 5G and 6G [95] at frequencies scarcely investigated up to now, e.g., mmWaves.

VII. CONCLUSION

This paper summarizes the characteristics and application domain of the main technologies used in the connected car, ranging from technologies for vehicle-to-everything connectivity to technologies for car sensing and intra-vehicle wireless connectivity. The paper also extensively describes the exposure field and the dose of EMF absorbed by passengers of cars equipped with such technologies, including the generic technologies for in-car personal connectivity (e.g., smartphones, tablets, etc.), as derived from current literature. All studies analyzed in the current survey evidenced that in no case the exposure field and the dose absorbed in car passengers were above the safe limits of exposure for the general population. Nevertheless, research on EMF exposure in the connected car shall address in the forthcoming years still open challenges to address more realistic scenarios and to consider aspects not yet investigated, such as simultaneous and combined exposure to field from multiple sources at different frequencies, the effect of the variability of the exposure scenario and the impact of new 5G and 6G technologies and very high frequencies in the mmWave band on EMF exposure in the car.

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GABRIELLA TOGNOLA received the master’s degree in Electronic Engineering and the Ph.D. degree in bioengineering, both from Politecnico di Milano, Milan, Italy. She is currently Senior Research Scientist with the Consiglio Nazionale delle Ricerche, Institute of Electronics, Computer and Telecommunication Engineering. Her main research interests include exposure assessment of electromagnetic fields with numerical dosimetry and with Machine Learning methods and modelling of electromagnetic fields for biomedical applications and innovative EMF applications in the connected vehicle.

MARTA BONATO (Student Member, IEEE) received the master’s degree in 2017 in Biomedical Engineering and the Ph.D. degree in Bioengineering in 2021 from the Politecnico of Milan, Milan, Italy. Since September 2017, she is with the Institute of Electronics, Computer, and Telecommunication Engineering, Consiglio Nazionale delle Ricerche, Rome, Italy, as Research Fellow. Her research interests include the study of the interaction of electromagnetic fields (EMF) with biological systems and the study of possible effects of EMF on health with both deterministic and stochastic dosimetry.

MARTINA BENINI received the B.S. degree in biomedical engineering in 2017 from the Alma Mater Studiorum – Università di Bologna (Italy) and the M.S. degree in biomedical engineering in 2020 from the Politecnico di Milano (Italy), where she is currently working toward the Ph.D degree in Bioengineering. From October 2020 to April 2021, she was a research fellow at the Consiglio Nazionale delle Ricerce (CNR), Institute of Electronics, Information Engineering and Telecommunication Networks (IETN). Her research interests are related to the study of the interaction between the electromagnetic fields (EMFs) and the human body with both deterministic and stochastic dosimetry, with the focus on the antennas used in the automotive field for vehicular connectivity.

SAM AERTS Sam Aerts was born in Sint-Niklaas, Belgium, in 1988. He received the M.Sc. degree in applied physics and the Ph.D. degree in electrical engineering from Ghent University, Ghent, Belgium, in 2011 and 2017, respectively. Since 2017, he has been a Postdoctoral Fellow with the Research Foundation–Flanders (FWO), Belgium, with the WAVES Research Group, Ghent University (UGent)-IMEC.

SILVIA GALLUCCI received the master’s degree in biomedical engineering from the University of Pisa, Pisa, Italy, in 2019. She is currently working toward the Ph.D. in bioengineering with the Politecnico di Milano, Milan, Italy, for studying the EMF–human interactions. From 2019 to 2020, she was a Research Fellow with the Institute of Electronics, Computer, and Telecommunication Engineering, Consiglio Nazionale delle Ricerche, Rome, Italy. Her main research focuses on the exposure...
assessment of electromagnetic fields with numerical dosimetry, particularly from 5G mobile communications.

**EMMA CHIARAMELLO** received the master’s and Ph.D. degrees in biomedical engineering from the Politecnico di Torino, Torino, Italy, in 2009 and 2013, respectively. She is a Research Scientist with the Institute of Electronics, Computer, and Telecommunication Engineering, National Research Council of Italy, Rome, Italy. Her research interests include the study of the interactions between EMF and biological systems, with both deterministic dosimetry based on computational electromagnetism methods and stochastic dosimetry based on surrogate modeling.

**SERENA FIOCCHI** received the master’s degree in biomedical engineering and the Ph.D. degree in bioengineering from the Polytechnic University of Milan, Milan, Italy, in 2009 and 2014, respectively. She is currently a Research Scientist with the Institute of Electronics, Computer, and Telecommunication Engineering, National Research Council of Italy, Rome, Italy. Her research interests include the study of the computational modeling of noninvasive brain and spinal stimulation techniques, the design and the optimization of biomedical technologies based on electromagnetic fields (EMF) for diagnostic and therapeutic applications, and the computational modeling of the interactions between EMF and biological systems.

**MARTA PARAZZINI** is currently a Research Scientist with the Institute of Electronics, Computer, and Telecommunication Engineering, Italian National Research Council, Rome, Italy. Her primary research interests include the study of the interactions of EMF with biological systems, deterministic and stochastic computational dosimetry, and the medical applications of EMF, in particular the techniques for noninvasive brain stimulation.

**BARBARA M. MASINI** (S’02–M’05–SM’19) is Senior Researcher at the National Research Council (CNR) of Italy in the Institute for Electronics and for Information and Telecommunications Engineering (IEIIT) and she is also adjunct Professor at the University of Bologna. She received the Laurea degree (summa cum laude) in Telecommunications Engineering and the Ph.D. degree in Electronic, Computer Science, and Telecommunication engineering from the University of Bologna, Italy, in 2001 and 2005, respectively. She works in the area of wireless communication systems and her research interests are mainly focused on connected vehicles, from physical and MAC levels aspects up to applications and field trial implementations. She received the best paper awards for research in the vehicular communications in 2017 at IEEE ITST Conference. She gave tutorials on V2X topics at ISWCS 2017 and WCNC 2019 and she served as invited speaker in several international events. She is Editor of IEEE Access and Computer Communication and she is responsible for a number of national and international projects on vehicular communications.

**WOUT JOSEPH** (M’05) was born in Ostend, Belgium on October 21, 1977. He received the M. Sc. degree in electrical engineering from Ghent University (Belgium) in July 2000. He obtained the Ph. D. degree in March 2005; this work dealt with measuring and modelling of electromagnetic fields around base stations for mobile communications related to the health effects of the exposure to electromagnetic radiation. He was from 2007-2012 a Post-Doctoral Fellow of the FWO-V (Research Foundation – Flanders). Since October 2009 he is professor in the domain of “Experimental Characterization of wireless communication systems.” He is IMEC PI since 2017. His professional interests are electromagnetic field exposure assessment, propagation for wireless communication systems, antennas and calibration. Furthermore, he specializes in wireless performance analysis and Quality of Experience.

**JOE WIART** (Senior Member, IEEE) is “Ingenieur general des Mines”, he received his Ph.D. degree, in 1995 and his HDR in 2015. Since 2015, he has been the holder of the Chair C2M “Characterization, modeling and Master of the Institut Mines Telecom” at Telecom Paris, Institut Polytechnique de Paris. He is also the Chairman of the TC106x of the CENELEC in charge of EMF exposure standards. He has been chair of URSI Commission K (electromagnetic fields and biological systems) between 2014 and 2021. His research interests include experimental, numerical methods, machine learning, artificial intelligence and statistic applied in electromagnetism and dosimetry. His works gave rise to more than 150 publications in journal articles and more than 200 communications.

**PAOLO RAVAZZANI** (Member, IEEE) received the master’s degree in electronic engineering and the Ph.D. degree in bioengineering from the Politecnico di Milano, Milan, Italy. He is currently the Director of Research with the Institute of Electronics, Computer, and Telecommunication Engineering, Consiglio Nazionale delle Ricerche, Rome, Italy. His main research interests include the exposure assessment of electromagnetic fields related to the study of the possible effects of electromagnetic fields on health and the biomedical applications of electromagnetic fields.