

Review

Research Progress on High-Frequency Electromagnetic Environments in the Internet of Vehicles

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Abstract

With the increasing demand for clean energy and low-carbon transportation, next-generation vehicles integrating high-frequency electronic systems have become more complex, raising concerns about in-vehicle electromagnetic exposure. This paper reviews high-frequency devices operating in the 30 kHz–300 GHz range and systematically analyzes the spatial distribution and key frequency characteristics of electromagnetic sources in vehicles. The results show that, even under worst-case conditions, electromagnetic exposure levels for occupants remain well below the safety limits defined by ICNIRP. For example, in a worst-case 5.9 GHz V2V communication scenario, the driver's head SAR_{10g} reaches 0.981 W/kg (9.81% of the ICNIRP occupational limit), while the whole-body SAR is only 0.008728 W/kg with negligible temperature rise. Other systems, including 5G-V2X, automotive radar, and mobile phones, also produce exposure levels far below safety thresholds. These findings suggest that RF exposure levels for vehicle occupants remain low relative to current guideline limits under the assessed scenarios. However, key challenges remain, including limited studies on multi-source exposure, insufficient data on vulnerable populations, simplified simulation conditions, lack of standardized validation methods, and inadequate assessment of emerging technologies. This work provides a quantitative basis for future safety standards and highlights critical research directions.

Keywords: V2X communication; RF electromagnetic exposure; specific absorption rate (SAR); millimeter-wave radar; in-vehicle wireless systems; multi-band RF coexistence; electromagnetic compatibility

1. Introduction

With the rapid advancement of modern technology, the automotive industry is undergoing a profound transformation from traditional mechanical products to intelligent mobile terminals. This evolution is mainly reflected in two aspects. On the one hand, powertrain systems are transitioning from internal combustion engines to electrified and hybrid configurations, leading to continuous optimization of the energy structure. On the other hand, in-vehicle electronic systems have evolved from simple radio and navigation devices into complex network architectures integrating vehicle-to-everything (V2X) communication, high-precision positioning, millimeter-wave radar, and multi-band mobile communication. These technological innovations have significantly enhanced vehicle intelligence and user experience.

Since the beginning of the 21st century, global vehicle ownership has increased steadily. In 2025, global vehicle sales reached 99.8 million units, demonstrating strong market vitality and growth potential [1]. Along with the rapid development of intelligent and connected



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vehicles, the in-vehicle electromagnetic environment has increasingly been shaped by radio frequency (RF) communication and sensing systems. Unlike conventional electromagnetic compatibility issues associated with vehicle powertrains and electrical components, high-frequency onboard RF systems operate over a wide frequency range, from several hundred MHz to tens of GHz, and generate complex electromagnetic exposure scenarios for vehicle occupants and nearby pedestrians. Therefore, high-frequency electromagnetic exposure associated with onboard RF antennas and wireless communication modules has become an important issue in automotive electromagnetic environment research.

In-vehicle RF antennas represent a critical source contributing to the complex high-frequency electromagnetic environment. The increasing penetration rate of onboard RF modules and the rapid adoption of intelligent vehicles imply a substantial expansion of the population exposed to high-frequency electromagnetic fields. Over the past century of fuel vehicle development, RF antennas have evolved from single low-frequency rod antennas for radio reception to densely distributed, multi-band, and multi-type antenna systems. Similarly, electric vehicles are undergoing a transition toward intelligence and connectivity. To support advanced autonomous driving and vehicle–road coordination, sub-6 GHz and mmWave 5G antennas [2,3], V2X communication antennas (5.9 GHz) [4], and RF modules integrated with LiDAR systems are being densely deployed, covering a wide frequency range from hundreds of MHz to tens of GHz [5,6]. The rapid proliferation of autonomous driving and the Internet of Vehicles is reshaping mobility patterns and enabling transformative innovations in traffic safety, efficiency, and infotainment [7]. However, it also introduces new electromagnetic exposure scenarios for vehicle occupants. Different types of onboard antennas, operating at various frequency bands, dynamically adjust transmission power in response to signal demands during driving, thereby generating electromagnetic radiation of varying frequencies and intensities in the surrounding space. This complex electromagnetic environment not only affects the reliability of vehicle electronic systems but also raises public concerns regarding long-term exposure safety. Available data indicate that the average daily driving duration for the general public is approximately 1–2 h on working days [8]. During this period, both vehicle occupants and nearby pedestrians are exposed to complex electromagnetic environments, which may pose potential health risks. Therefore, investigating the impact of automotive electromagnetic environments on human health is of considerable importance.

As key components enabling information exchange between vehicles and the external environment, onboard RF antennas exhibit strong functional and technical commonalities across different vehicle types. Moreover, most existing studies on RF electromagnetic exposure do not explicitly distinguish between vehicle categories. Therefore, this paper provides a unified discussion of electromagnetic exposure from onboard RF antennas without deliberately differentiating between fuel vehicles and electric vehicles. Focusing on RF-based in-vehicle wireless communication systems shared by both vehicle types, which operate within the RF spectrum for external information interaction, this paper systematically reviews research progress on automotive RF electromagnetic exposure. It further summarizes studies on the health effects of electromagnetic exposure and relevant international standards, analyzes the structural characteristics, measurement methods, and actual exposure levels of RF sources in vehicles, and quantitatively evaluates exposure levels and associated health risks. The aim is to provide a theoretical basis for future standard updates and public health assessments.

The remainder of this paper is organized as follows. Section 2 describes the review methodology. Section 3 introduces the classification and operational characteristics of high-frequency radiation sources. Section 4 summarizes representative studies on electromagnetic exposure safety assessment of in-vehicle high-frequency devices. Section 5

presents the main conclusions, discusses existing challenges and limitations in current research on automotive electromagnetic exposure, and outlines future research directions.

2. Review Methodology

A structured literature-search and study-selection strategy was adopted to improve the transparency and reproducibility of this review. The purpose of the methodology was to identify representative studies on high-frequency electromagnetic exposure associated with in-vehicle RF wireless communication and sensing systems, with particular attention to exposure sources, assessment methods, dosimetric quantities, and compliance with international exposure limits.

2.1. Literature Search Strategy

Relevant studies were identified through searches of four major academic databases: IEEE Xplore, PubMed, Web of Science and Scopus. These databases were selected to cover both engineering-oriented studies on vehicular antennas, wireless communication systems, and automotive radar, as well as biomedical and public-health studies related to RF electromagnetic exposure, SAR assessment, and dosimetry. IEEE Xplore was primarily used to retrieve studies on V2X communication, vehicular antennas, mmWave radar, RF engineering, and antenna-system design. PubMed was used to identify studies related to RF electromagnetic exposure, biological dosimetry, SAR evaluation, thermal effects, and public-health assessment. Web of Science and Scopus were used to provide broader interdisciplinary coverage and to identify citation-linked studies across engineering, biomedical, environmental, and communication-related fields.

The literature search covered publications from January 2000 to March 2026. The search period was selected to capture the rapid development of in-vehicle wireless systems, from early RF and navigation systems to recent V2X, 5G-V2X, Wi-Fi, GNSS, and mmWave radar technologies. Searches were performed using database-specific syntax where necessary, and the search terms were adapted according to the indexing rules of each database.

2.2. Search Terms

The search strategy combined terms related to vehicular RF sources with terms related to electromagnetic exposure assessment. The following representative search terms and keyword combinations were used:

- “Vehicle electromagnetic exposure”;
- “Automotive RF exposure”;
- “In-vehicle RF-EMF”;
- “V2X electromagnetic exposure”;
- “5.9 GHz V2X SAR”;
- “5G-V2X SAR”;
- “Automotive radar exposure”;
- “Millimeter-wave radar exposure”;
- “GNSS antenna exposure”;
- “SAR ICNIRP vehicle”;
- “RF electromagnetic exposure connected vehicles”;
- “Vehicle wireless communication antennas”.

To improve retrieval coverage, Boolean operators were applied where appropriate. For example, terms related to vehicle systems, such as “vehicle”, “automotive”, “connected vehicle”, “V2X”, “GNSS”, “Wi-Fi”, and “automotive radar”, were combined with exposure-related terms, including “electromagnetic exposure”, “RF-EMF”, “SAR”, “power density”, “electric field”, “temperature rise”, “ICNIRP”, and “IEEE exposure limits”. Search terms

will be further refined where necessary to ensure coverage of emerging technologies and recent exposure-assessment studies.

2.3. Eligibility Criteria

Studies were considered eligible if they met at least one of the following criteria:

- (i) the study investigated RF or high-frequency electromagnetic sources associated with vehicles or in-vehicle wireless systems;
- (ii) the study focused on V2X, 5G-V2X, GNSS, Wi-Fi, mobile communication, or automotive radar systems;
- (iii) the study reported quantitative exposure-related metrics, such as electric field strength, magnetic field strength, specific absorption rate, absorbed power density, incident power density, or temperature rise;
- (iv) the study compared exposure levels with international guidelines or standards, such as those issued by ICNIRP or IEEE; or
- (v) the study provided relevant information on RF source characteristics, antenna configurations, exposure scenarios, measurement methods, numerical simulation methods, or health-related exposure assessment.

Studies were excluded if they met any of the following criteria:

- (i) they focused exclusively on low-frequency powertrain-related sources, such as electric motors, inverters, high-voltage cables, or electric-drive systems;
- (ii) they discussed general electromagnetic compatibility without providing information relevant to RF source characterization or human exposure assessment;
- (iii) they investigated base stations, mobile phones, or indoor communication systems without a clear vehicular or in-vehicle scenario;
- (iv) they lacked clearly specified operating frequency, RF source type, exposure object, or source-characterization information relevant to this review;
- (v) they were duplicate records;
- (vi) full-text access was unavailable; or
- (vii) they were not written in English.

2.4. Study Selection, Data Extraction, and Quality Assessment

The study-selection process consisted of four steps: database identification, duplicate removal, title and abstract screening, and full-text eligibility assessment. First, records were retrieved from Web of Science, Scopus, IEEE Xplore, and PubMed. Duplicate records were then removed. The remaining records were screened by title and abstract to exclude studies outside the scope of vehicular or in-vehicle RF electromagnetic exposure. Full texts were subsequently assessed according to the eligibility criteria.

The final evidence base included 57 studies for qualitative source characterization, of which 16 studies reported quantitative exposure values and were included in the comparative exposure-assessment summary.

For each included study, the following information was extracted where available: source type, operating frequency, antenna location, transmission power or source parameter, exposure scenario, human model or measurement position, numerical or experimental method, exposure duration, dosimetric quantity, maximum exposure value, comparison with ICNIRP or IEEE limits, and main conclusions.

The methodological quality of the included exposure-assessment studies was evaluated using an engineering-oriented checklist adapted to RF exposure studies. The assessment considered whether each study clearly specified the RF source type and operating frequency, antenna position and transmission power, human model or measurement location, exposure metrics, comparison with ICNIRP or IEEE limits, validation proce-

ture, uncertainty analysis, and consideration of multi-source exposure or potentially vulnerable populations.

Because the included studies differed substantially in source type, frequency band, antenna configuration, exposure scenario, human model, and dosimetric endpoint, a meta-analysis was not performed. Instead, the evidence was synthesized narratively and comparatively according to source category, including V2X communication antennas, 5G-V2X systems, automotive radar, mobile communication devices, and other in-vehicle short-range wireless systems. Exposure levels were compared with current ICNIRP or IEEE limits where applicable.

3. Classification and Characteristics of In-Vehicle High-Frequency Electromagnetic Exposure Sources

Onboard antennas constitute one of the primary sources of electromagnetic radiation within the complex in-vehicle electromagnetic environment. With the advancement of vehicle intelligence, onboard wireless communication systems have gradually formed a comprehensive technological framework, including vehicle-to-everything (V2X) communication systems, Global Navigation Satellite System (GNSS), mobile communication systems, Bluetooth modules, and automotive radar [9], as illustrated in Figure 1. In contrast, GNSS/navigation antennas primarily function as passive receiving devices and should be distinguished from active RF transmitters, although their installation sites remain relevant to vehicle-level electromagnetic compatibility and antenna integration. The main radiation sources of onboard wireless systems and their operating frequency bands are summarized in Table 1.

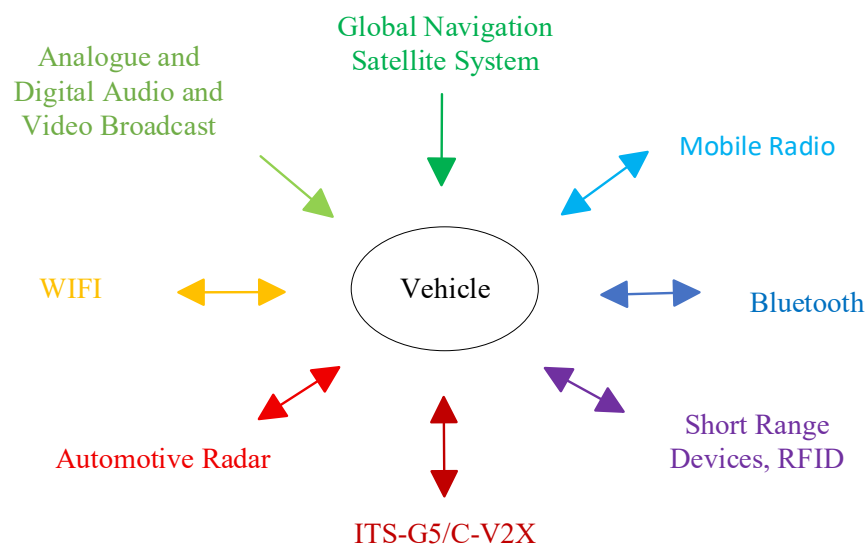


Figure 1. Composition of onboard wireless communication systems.

3.1. V2X (5.9 GHz) Communication Antennas

Vehicle-to-everything (V2X) refers to communication technologies that enable vehicles to exchange information with all relevant entities in their surroundings. It encompasses multiple communication modes, including vehicle-to-vehicle (V2V), vehicle-to-infrastructure (V2I), vehicle-to-pedestrian (V2P), and vehicle-to-network (V2N).

V2I communication enables real-time data exchange with roadside units (RSUs), allowing vehicles to obtain traffic signal phase and timing information for speed guidance and coordinated signal passage. V2V communication operates via 5.9 GHz dedicated short-range communication (DSRC) or cellular V2X (C-V2X) protocols, supporting low-latency applications such as emergency braking warnings. V2P communication leverages LTE/5G-

enabled smart devices to enhance pedestrian safety, while V2N communication relies on cellular networks to provide cloud-based services, including real-time high-definition map updates. As a key component, V2X antennas enable wireless connectivity, remote diagnostics, and safety-critical warning functions. It has been reported in [10] that V2X technology can prevent collisions by exchanging parameters such as speed and direction, while also optimizing routes using information from road infrastructure and surrounding vehicles. The core value of V2X lies in improving traffic safety, enhancing transportation efficiency, and providing reliable information exchange for autonomous driving.

V2X communication primarily operates in the 5.9 GHz frequency band. Currently, two dominant technological approaches exist: DSRC based on IEEE 802.11p [11] (referred to as ITS-G5 in Europe) and cellular-based C-V2X [12]. As reported in [13], C-V2X was standardized by 3GPP in Release 14 and is evolving toward 5G New Radio (NR), supporting low-latency and high-reliability applications such as vehicle platooning, advanced driving, and extended sensing. Meanwhile, [14] emphasizes that DSRC/ITS-G5 remains a key candidate technology for V2X and should be integrated with cellular networks to leverage complementary advantages.

The deployment of V2X antennas directly affects communication reliability. Due to continuous changes in communication direction during vehicle motion, antennas are required to provide approximately omnidirectional coverage in the horizontal plane. Common installation locations include shark-fin roof modules, rearview mirrors, and bumpers. As shown in Figure 2a, [15] presents a design in which the V2X antenna is integrated within a shark-fin module, where multiple antennas (e.g., V2X, LTE, and GPS) are compactly arranged within a plastic housing, utilizing the metallic vehicle roof as a ground plane to achieve horizontal omnidirectional coverage within limited space. Figure 2b further provides a vehicle-level installation view of the shark-fin antenna, showing its typical roof-mounted configuration in practical passenger-vehicle applications. In addition, [16] proposes a monopole antenna fabricated using 3D metal bending technology, enabling multi-band operation including 5.9 GHz within a compact structure, which is suitable for cost-effective mass production.

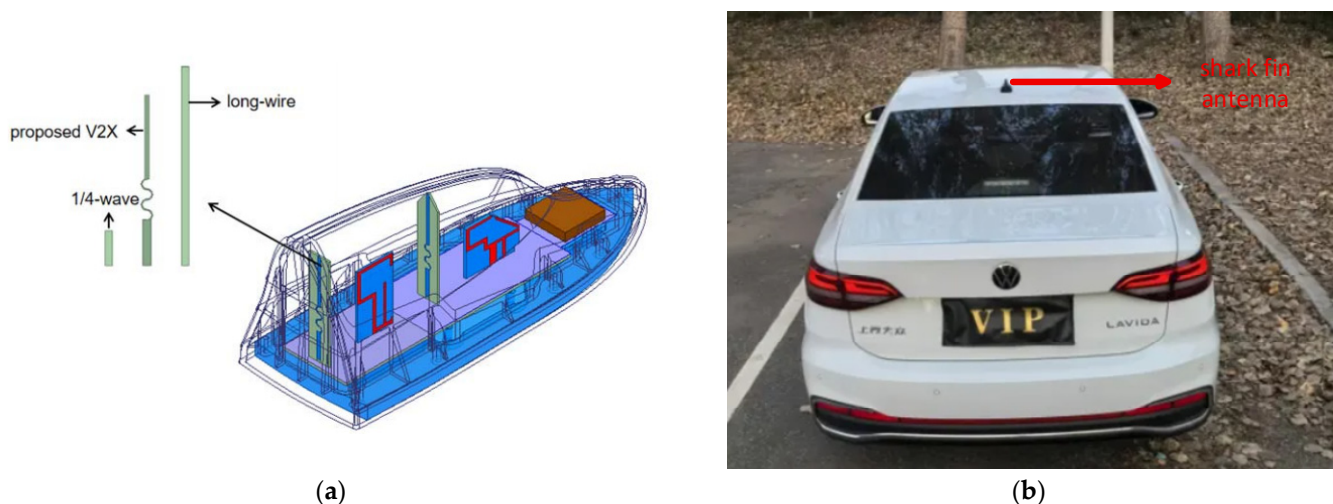


Figure 2. (a) A shark-fin vehicular V2X antenna model. The green vertical plates represent the FR4 substrates carrying the V2X radiating elements. The red conductive patterns and blue plates represent the LTE antenna radiators and their PCB substrates, respectively. The orange block represents the GPS antenna, the blue horizontal base represents the common metallic ground plane, and the transparent enclosure represents the shark-fin radome; (b) Photograph of a shark-fin antenna mounted on a vehicle.

To mitigate signal blockage caused by vehicle metallic pillars, multi-antenna diversity techniques are widely adopted. In [10], maximum ratio combining using spatially separated antennas is proposed to effectively eliminate coverage blind spots of a single antenna. Furthermore, [17] introduces metamaterial structures to reduce mutual coupling between antennas, thereby improving isolation in multiple-input multiple-output (MIMO) systems. Circularly polarized antennas have also attracted attention due to their improved signal stability in dynamic environments. In [18], a compact circularly polarized antenna is designed, achieving an axial ratio better than -3 dB at 5.9 GHz, making it suitable for high-mobility vehicular scenarios.

3.2. 5G-V2X Communication Antennas

With the evolution of intelligent connected vehicles toward higher levels of autonomous driving and vehicle–road coordination, conventional vehicular communication technologies are undergoing significant upgrades. Early vehicular networks primarily relied on IEEE 802.11p (or its European counterpart ITS-G5) and LTE-based cellular V2X (LTE-V2X) to support fundamental safety-related information exchange, such as collision warnings and traffic signal notifications. However, as application scenarios expand from basic safety services to advanced use cases—including high-level autonomous driving, real-time high-definition video sharing, cooperative perception with extended sensors, and remote driving—the requirements for data rate, latency, and link reliability have become substantially more stringent. Due to limitations in system bandwidth and frame structure, LTE-V2X is no longer sufficient to fully meet these enhanced performance demands [13].

Against this background, the Third Generation Partnership Project (3GPP) formally introduced cellular V2X communication based on 5G New Radio (NR), namely 5G NR V2X, in Release 16. Rather than completely replacing LTE-V2X, 5G-V2X is designed to coexist with and complement existing systems: LTE-V2X continues to support basic road safety services, while 5G-V2X targets more demanding scenarios such as high-level autonomous driving, vehicle platooning, and remote operation [13]. A key advantage of 5G-V2X lies in its support for unicast, multicast, and broadcast communication modes, enabling end-to-end latency at the millisecond level and data transmission reliability of up to 99.999%. These capabilities are essential for achieving precise cooperative control among vehicles in autonomous driving scenarios.

Unlike conventional V2X technologies, which primarily operate in the 5.9 GHz band, 5G-V2X significantly expands the available spectrum resources. According to 3GPP specifications, 5G-V2X can operate in two frequency ranges: Frequency Range 1 (FR1, 410 MHz–7.125 GHz) and Frequency Range 2 (FR2, 24.25–52.6 GHz) [13,19]. The lower-frequency FR1 band provides favorable wide-area coverage and diffraction capabilities, ensuring robust baseline communication. In contrast, the mmWave bands within FR2 (e.g., n257: 26.5–29.5 GHz and n260: 37–40 GHz) offer abundant contiguous spectrum resources, supporting gigabit-level data rates and enabling high-capacity information exchange between vehicles and 5G base stations, as well as among vehicles [20,21].

In practical deployments, 5G-V2X antennas are typically installed at locations such as shark-fin roof modules, windshields, or rear roof sections [19,21]. The selection of installation positions must balance multiple considerations: ensuring adequate beam coverage toward surrounding vehicles and roadside infrastructure, minimizing interference from metallic vehicle components, and satisfying aerodynamic and industrial design constraints.

Given the limited installation space available in vehicles, integrating multiple operating frequency bands within a single antenna structure has become a key design direction for 5G-V2X antennas [20,22]. Figure 3 illustrates a representative multi-band shared-aperture hybrid array antenna structure [21]. In this design, a 5.9 GHz microwave V2X antenna

is physically integrated with a mmWave antenna array operating at 28 GHz and 39 GHz. Specifically, the microwave patch elements are arranged in the outer layer, while the mmWave array is embedded within the inner structure. This shared-aperture configuration significantly reduces the overall antenna footprint while simultaneously improving performance through structural integration.

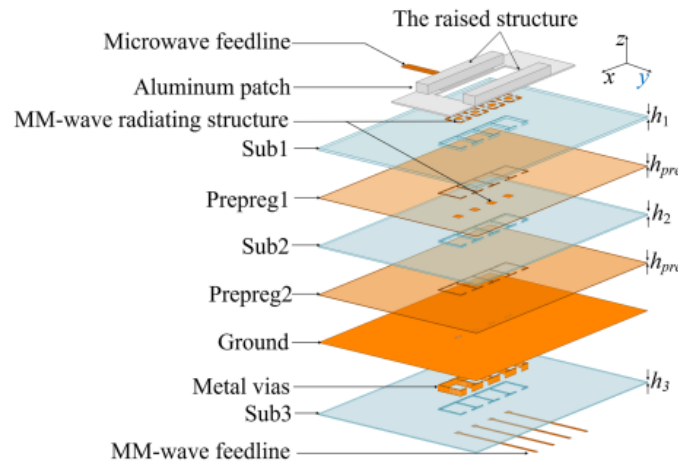


Figure 3. Schematic diagram of a multi-band shared-aperture 5G-V2X antenna structure. The light-blue layers represent the Rogers 4003 substrates (Sub1–Sub3), the light-orange layers represent the Rogers 4350 prepreg bonding layers, the gray upper structure represents the aluminum V2X patch and its raised section, and the orange metallic parts represent the ground plane, feedlines, millimeter-wave radiating structures, and metal vias.

In addition to shared-aperture designs, array-based configurations are widely employed to enhance antenna gain and compensate for the high path loss associated with mmWave propagation. In [23], a series-fed patch antenna array is extended to a nine-element configuration, achieving a gain exceeding 15 dBi and a sidelobe level below -17 dB at 28 GHz, providing a compact and efficient solution for high-data-rate mmWave communication. From a system-level perspective, [24] proposes a three-dimensional antenna architecture in which microwave and mmWave elements are distributed across horizontal and vertical substrates, forming a multi-beam MIMO system capable of achieving full 360° azimuthal coverage around the vehicle in both frequency bands.

Furthermore, in complex vehicular environments, joint beamforming capabilities in both the horizontal and vertical planes represent another important approach for addressing multidimensional communication scenarios. In the work of Islam et al. [25], a circular antenna array configuration is employed, where beam steering in the horizontal plane is achieved by controlling the excitation phase of individual antenna elements. Additionally, reconfigurable radiating elements are introduced, utilizing switching components such as PIN diodes to enable end-fire operation modes, thereby generating beams with different elevation angles in the vertical plane. This design ultimately achieves full 360° spatial coverage around the vehicle, providing robust communication support in complex environments such as urban canyons and multi-level interchanges.

Recent studies on vehicular edge computing further suggest that the effective RF emission characteristics of future IoV systems may be determined not only by antenna hardware but also by system-level power-control and beam-management strategies. Ju et al. [26] proposed a NOMA- and hybrid-beamforming-aided secure computation offloading framework for mmWave VEC networks, in which the analog beamforming matrix, user-vehicle transmit power, and MEC computation-resource allocation ratio were jointly optimized using a multi-agent DRL scheme. Similarly, a recent study on fluid-antenna-assisted MEC

networks jointly considered channel estimation, fluid-antenna port selection, beamforming, user power control, and MEC resource allocation within a unified optimization framework [27]. Although these studies do not directly report human exposure quantities, such as SAR, absorbed power density, incident power density, or temperature rise, they indicate that adaptive power control and directional beam management may become important system-level factors influencing the temporal and spatial distribution of RF fields around intelligent connected vehicles.

3.3. Positioning and Navigation Antennas

Automotive positioning and navigation antennas are discussed together because vehicle navigation functions fundamentally rely on GNSS-based positioning and timing. These antennas receive satellite signals from systems such as GPS, BeiDou, Galileo, and GLONASS, thereby providing vehicles with position, velocity, and time information required for route guidance, autonomous driving, and vehicle–road coordination. In contrast to V2X, 5G-V2X, and radar antennas, GNSS/navigation antennas are passive receiving devices and do not normally act as primary RF exposure sources. Nevertheless, their installation sites and electromagnetic compatibility remain relevant to whole-vehicle RF system integration and exposure assessment.

The operating frequencies of in-vehicle positioning and navigation antennas are mainly concentrated in the GNSS L1 band, approximately 1575.42 MHz, and L2 band, approximately 1227.60 MHz; newer designs also support the L5 band at 1176.45 MHz to improve positioning robustness and multipath mitigation [28]. To ensure compatibility with multiple satellite-navigation systems, modern antenna modules commonly adopt wideband or multiband configurations. For example, compact modules can cover 1559–1610 MHz and 1227–1237 MHz within a 43 mm × 43 mm volume, while achieving a right-hand circularly polarized (RHCP) gain of 4.5 dBi in the zenith direction and cross-polarization suppression better than 16 dB [29]. Figure 4a [30] illustrates a typical automotive navigation antenna module with multiple radiating elements integrated into a low-profile structure, while Figure 4b [30] shows a roof-mounted shark-fin installation commonly used in passenger vehicles.

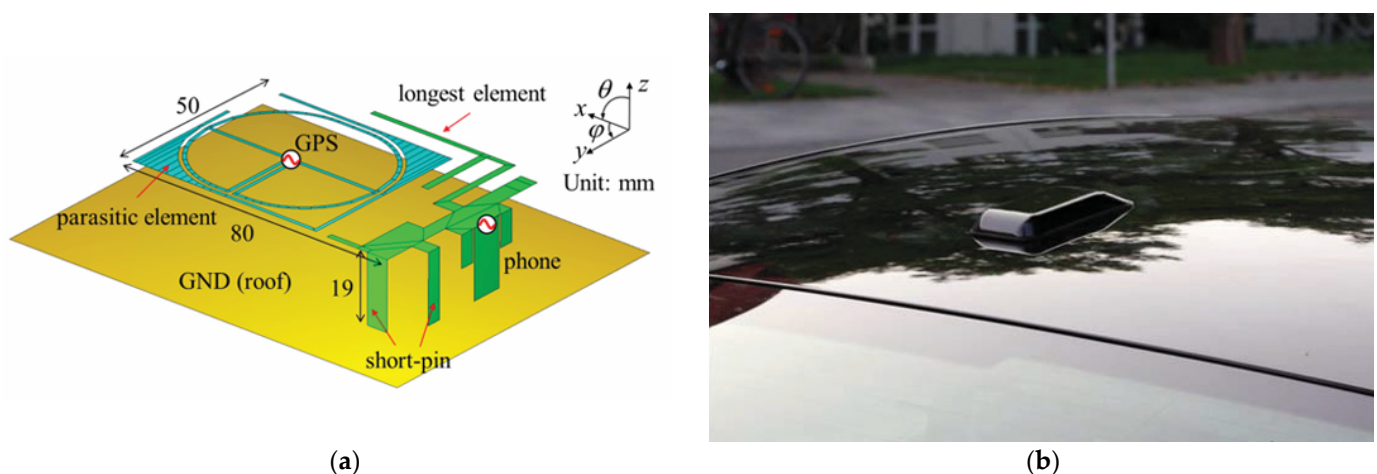


Figure 4. (a) A typical automotive navigation antenna module; (b) Installation of a navigation antenna within a roof-mounted shark-fin enclosure.

In practical vehicle platforms, positioning and navigation antennas are usually installed in the rear-central region of the roof or near the rear windshield, where a relatively unobstructed sky view can be obtained and signal blockage caused by the metallic vehicle body can be reduced [28]. Other designs distribute antenna elements within the left and

right side mirrors to form an L-shaped subarray, thereby using existing vehicle structures while avoiding excessive antenna concentration on the roof [31]. In recent years, multi-antenna fusion has become an important approach for improving positioning accuracy. For instance, tightly coupling multiple GNSS antennas with an inertial navigation system (INS), while exploiting a shared clock to eliminate receiver clock bias, can reduce horizontal positioning error by more than 40% [32]. Base-station-free differential positioning methods can estimate vehicle position using fixed geometric constraints among antennas and achieve lane-level accuracy in open environments [33]. In urban canyons, joint estimation algorithms that simultaneously account for antenna attitude, channel inconsistency, and multipath signals can maintain positioning availability without precise pre-calibration [34].

Antenna miniaturization and vehicle-body integration are also important trends. GNSS antenna modules are generally characterized by compact size, low weight, low power consumption, and strong anti-interference capability [35]. Taking the compact dual-frequency circularly polarized antenna proposed by Zhong et al. as an example [36], Figure 5a shows that miniaturization can be achieved through a stacked dual-patch configuration combined with four coupled metallic posts, whereas Figure 5b illustrates a typical vehicle-level application of a GNSS antenna mounted on an intelligent vehicle platform. Other representative designs include triple-band antennas based on U-shaped and inverted H-shaped slots, covering 1.06–1.23 GHz, 1.23–1.39 GHz, and 1.53–1.65 GHz [37]; wideband antennas using shorting techniques to split the dominant TM₁₀ mode and operate over 1.1–1.6 GHz [38]; and patch antennas with rectangular slots and diagonal corner truncation, which can achieve an axial ratio of 1.19 dB within the 1.559–1.606 GHz band [39].

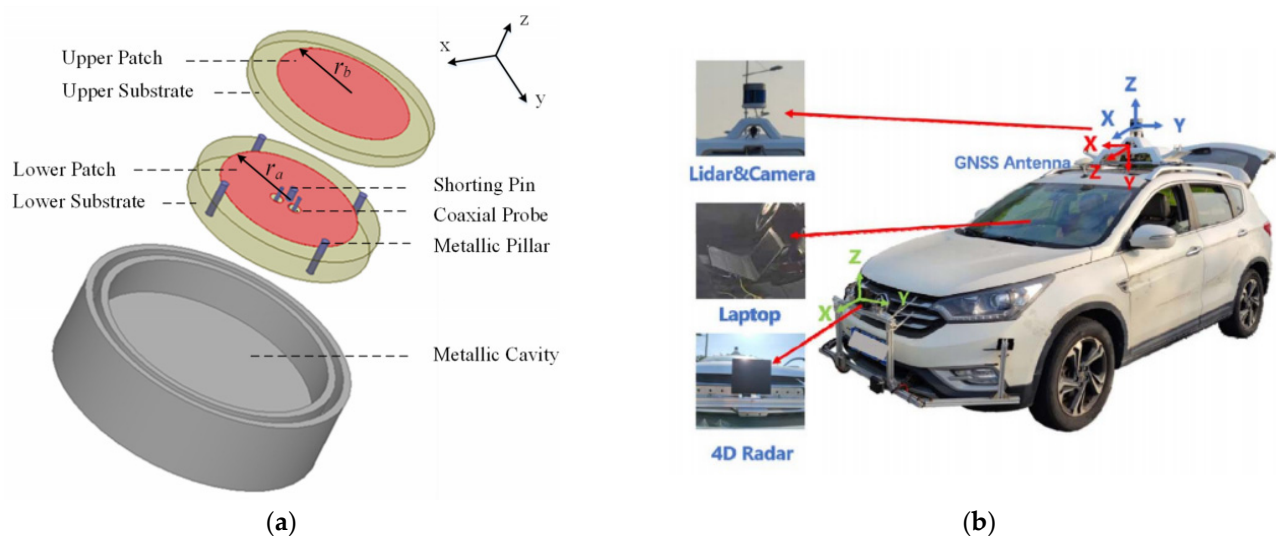


Figure 5. (a) Exploded view of a typical vehicular navigation antenna (from top to bottom: upper patch for L1 band, upper dielectric substrate, lower patch for L2 band, four metallic posts, central shorting pin, lower dielectric substrate, feeding network, and modified circular cavity-backed structure); (b) Typical application of a vehicular GNSS antenna.

Although positioning and navigation antennas do not actively transmit high-power RF signals, they are sensitive to the surrounding electromagnetic environment. With the increasing number of in-vehicle wireless services, such as mobile communication, GPS, Bluetooth, and V2V, the number of antennas installed in automobiles has also increased [40], which may lead to electromagnetic interference and degrade GNSS reception performance or positioning accuracy. At the same time, the close coexistence of GNSS/navigation antennas with active antennas such as V2X and 5G systems makes antenna integration and local field distribution relevant to vehicle-level exposure assessment. Recent roof-

and windshield-integrated designs further illustrate this trend. For example, a coplanar waveguide-fed circularly polarized antenna embedded in laminated glass can cover 1.16–1.606 GHz, including the L5, L2, and L1 bands [41], while transparent metallic-mesh antennas can maintain high optical transparency and achieve a 3 dB axial-ratio bandwidth over 1.06–1.72 GHz when accounting for windshield inclination [42]. To suppress multipath interference, navigation antennas commonly rely on RHCP, and some designs can dynamically steer the circular-polarization direction by adjusting the phase difference between dual orthogonal feed ports within 78–102°, thereby maintaining high polarization purity within a beamwidth of 83° [43]. Therefore, although GNSS/navigation antennas are not dominant RF emitters, their passive receiving function, installation location, integration with active RF systems, and susceptibility to electromagnetic interference should still be considered in whole-vehicle electromagnetic exposure and compatibility assessments.

3.4. Automotive Radar

The concept of automotive radar can be traced back to the 1960s, when researchers proposed the use of radar for vehicle speed measurement and obstacle detection to assist drivers in emergency braking scenarios [44]. After several decades of development, automotive radar has been commercialized since 1999 and has gradually become a core sensor in intelligent driving systems [45]. At present, automotive collision-avoidance radar operates by transmitting and receiving electromagnetic waves at specific frequencies, enabling real-time perception of the surrounding environment and providing essential data for functions such as automatic emergency braking and adaptive cruise control.

Automotive radar primarily operates in the mmWave frequency bands, with typical ranges including 24 GHz and 77/79 GHz. The 24 GHz band is commonly used for short-range detection and is widely applied in scenarios such as blind-spot monitoring and lane-change assistance [46]. In contrast, the higher-frequency 77/81 GHz bands, benefiting from larger bandwidth and improved resolution, have become the mainstream choice for medium- and long-range radar systems [45], while next-generation short- and medium-range sensors are also being deployed within the 77–81 GHz range [47,48]. To meet diverse detection requirements, automotive radar systems are generally categorized into short-, medium-, and long-range radars, each playing a distinct role in applications such as collision warning, lane-change assistance, and adaptive cruise control [46]. In terms of waveform design, frequency-modulated continuous wave (FMCW) is the most widely adopted scheme, owing to its compact architecture, low peak power, and capability for simultaneous range and velocity measurement, making it well suited to the resource constraints of vehicular platforms [49].

Figure 6a illustrates an eight-element series-fed microstrip array antenna, in which the radiating patches, dielectric substrate (thickness of 0.254 mm), ground plane, and lumped port structure are clearly presented. Such designs can achieve gains exceeding 20 dBi with low sidelobe levels within limited vehicular installation space, thereby satisfying the requirements for angular resolution and detection range in lateral collision warning applications.

Compared with other in-vehicle sensors, mmWave radar exhibits a significant advantage in all-weather operation. Under adverse conditions such as rain, snow, fog, dust, or low-light environments (e.g., nighttime), its perception performance is markedly superior to that of cameras and LiDAR, making it an indispensable sensing modality [50,51]. In terms of installation, automotive radar is typically mounted behind the bumper to protect electronic components from debris and moisture, while radar signals can still propagate effectively through non-metallic materials [46]. However, such embedded installations

may introduce the risk of misalignment due to long-term vibrations or minor collisions, potentially degrading sensing accuracy and posing safety concerns.

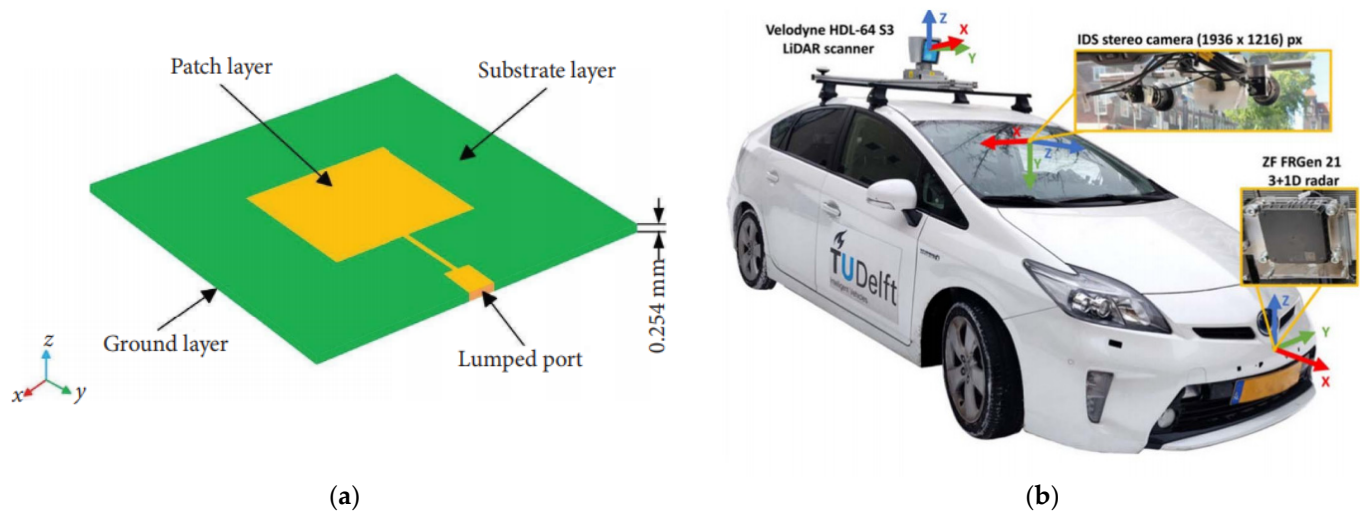


Figure 6. (a) Typical 24 GHz automotive radar microstrip antenna element structure; (b) Schematic diagram of a typical radar antenna.

To accommodate increasingly complex autonomous driving requirements, automotive radar is evolving toward higher precision and integration. On the one hand, antenna design is transitioning from traditional lens and reflector antennas to compact, low-profile planar array antennas to meet stringent constraints on size and cost for vehicular integration [45,52]. On the other hand, advanced techniques such as multiple-input multiple-output (MIMO) have been introduced, significantly enhancing angular resolution and imaging capability by integrating higher-density antenna channels at the chip and package levels. High-resolution 4D imaging radar can simultaneously provide range, azimuth, elevation, and velocity information within a single frame [53,54]. These technological advancements have enabled automotive radar to evolve from a single-function warning sensor into an intelligent perception node capable of target classification, contour estimation, and even environmental imaging, thereby providing a solid foundation for high-level autonomous driving safety [48].

To support the development of perception algorithms and electromagnetic exposure assessment, researchers have established multi-sensor data acquisition platforms under near-real deployment conditions. Figure 6b presents a representative multi-sensor configuration for autonomous vehicles, including a Velodyne HDL-64 S3 LiDAR, an IDS stereo camera, and a ZF FRGen 21 3+1D radar (a type of 4D mmWave radar). This configuration originates from the “View-of-Delft” dataset developed by Delft University of Technology (TU Delft) [51] and is widely used in multimodal perception studies for complex urban traffic scenarios.

In summary, automotive radar operates across a wide frequency range from 24 GHz to 81 GHz. Owing to its all-weather robustness, accurate range and velocity measurement capabilities, and increasingly advanced imaging performance, it has become an indispensable sensor in intelligent connected vehicles. Notably, these radar modules continuously radiate electromagnetic energy during operation, constituting one of the primary sources of high-frequency electromagnetic exposure for vehicle occupants.

3.5. In-Vehicle Wireless Communication Antennas

In-vehicle wireless communication antenna modules integrate multiple communication functions, including Wi-Fi, cellular communication, and Bluetooth, and serve as core

components for enabling connectivity and interaction in intelligent vehicles [55]. Cellular communication antennas utilize both sub-6 GHz and mmWave (24.25–52.6 GHz) frequency bands in 4G/5G systems [56] to support wide-area data connectivity [57,58].

Wi-Fi antennas operate in the 2.4 GHz and 5 GHz bands to establish in-vehicle local area networks, while Bluetooth antennas function within the 2.4–2.485 GHz band to enable short-range device pairing and data exchange [59].

When operating concurrently across multiple frequency bands, the antenna module typically employs techniques such as frequency division multiplexing (FDM) and time division multiplexing (TDM) to mitigate mutual interference. However, this also leads to complex electromagnetic radiation characteristics, including multi-frequency superposition and dynamic temporal variations.

Table 1. Major RF systems and antenna modules in in-vehicle wireless communication and sensing systems.

RF Systems and Antenna Modules	Frequency	References
ITS-G5/C-V2X	5.9 GHz	[60–63]
5G-V2X	410 MHz–7.125 GHz/24.25–52.6 GHz	[19,64]
GNSS /navigation receiving antenna module	1559–1610 MHz/1227–1237 MHz	[28]
Automotive Radar	24–100 GHz	[65–70]
Wi-Fi	2.4 GHz/5 GHz	[9,71]
Bluetooth	2.4–2.485 GHz	[9,62,72]
Mobile Radio	900 MHz/1800 MHz/Sub-6 GHz/24.25–52.6 GHz	[62,72–77]

4. Electromagnetic Exposure Safety Assessment of In-Vehicle RF Wireless Networking Systems

In-vehicle wireless networking systems, including V2X, GNSS, cellular communication, and mmWave radar modules, operate within the RF range addressed by major exposure guidelines, while the reviewed sources are mainly distributed from the MHz to mmWave bands. Vehicular GNSS/navigation antennas are not treated as primary RF exposure sources in the quantitative exposure synthesis because they normally operate as passive receiving devices. Accordingly, GNSS/navigation antennas are discussed in Section 2 in relation to positioning functionality, antenna integration, and electromagnetic compatibility, rather than as active sources of RF exposure. The absorption of RF electromagnetic fields (RF-EMF) by the human body may lead to tissue heating. Therefore, exposure limits recommended by the International Commission on Non-Ionizing Radiation Protection (ICNIRP) and the Institute of Electrical and Electronics Engineers (IEEE) are designed to restrict both local and core body temperature increases within safe thresholds.

Before summarizing the reviewed exposure-assessment studies, the applicability of exposure metrics across frequency ranges should be clarified, because SAR, absorbed power density, incident power density, temperature rise, and reference field levels are not interchangeable quantities, as shown in Table 2. In general, below 6 GHz, whole-body averaged SAR (SAR_{wb}) and localized SAR, such as SAR averaged over 10 g of tissue (SAR_{10g}), are the principal dosimetric quantities. Above 6 GHz, absorbed power density becomes the central quantity for localized exposure assessment. Incident power density, electric field strength, magnetic field strength, and other externally measurable quantities

are generally used as reference levels or practical assessment quantities, depending on the applicable standard, frequency range, and exposure scenario.

Table 2. Applicability of exposure metrics and limit quantities across frequency ranges.

Frequency Range	Main Basic Restriction/Dose Quantity	Reference Levels/Practical Quantities	Typical Metrics in Reviewed Studies	Notes
100 kHz–6 GHz	Whole-body SAR and localized SAR	External E-field, H-field, and incident power density where applicable	SAR _{wb} , SAR10g, SAR1g, E-field, temperature rise	Relevant to 5.9 GHz V2X, 5G-V2X FR1, mobile communication, Wi-Fi, and similar sub-6 GHz RF sources.
>6–300 GHz	Absorbed power density for localized exposure	Incident power density and external field quantities as reference or screening	Absorbed power density, incident power density, E-field, temperature rise	Relevant to 5G-V2X FR2, automotive radar, mmWave communication, and other mmWave sources. Incident power density should be distinguished from absorbed power density.
All RF ranges	Temperature rise as a thermal-effect endpoint	Used to interpret the thermal relevance of exposure metrics	Temperature increase or tissue heating	Compliance with thermal-effect limits should not be interpreted as the absence of all possible health effects.

In this context, SAR and absorbed power density represent internal dosimetric quantities or basic restrictions, whereas incident power density and external electric or magnetic field strength are externally measurable reference or screening quantities. Temperature rise is a thermal-effect endpoint used to interpret the biological relevance of absorbed energy. Therefore, these quantities are physically related through electromagnetic absorption and tissue heating, but they cannot be directly substituted for one another in compliance assessment.

In addition, compliance assessment should consider the prescribed temporal and spatial averaging requirements of the applicable standard; for example, under ICNIRP 2020, whole-body averaged SAR is averaged over 30 min, whereas localized SAR and absorbed power density are averaged over 6 min, with localized SAR averaged over 10 g of tissue and absorbed power density generally averaged over 4 cm² of body surface.

For multi-source and multi-frequency vehicular exposure scenarios, exposure quantities should not be directly compared across incompatible physical metrics, such as SAR, electric field strength, incident power density, absorbed power density, and temperature rise. Instead, each source should first be assessed using the frequency-appropriate basic restriction or reference level and then normalized to the corresponding limit. This approach is consistent with previous multi-source vehicular exposure studies. Schilling et al. [9] evaluated several in-vehicle wireless systems, including ITS-G5, Bluetooth, and Wi-Fi, by expressing the measured field levels as fractions of the ICNIRP reference level. Yang et al. [62] further defined a cumulative exposure index for V2X and in-vehicle wireless technologies, in which the maximum electric field strength below 2 GHz and the maximum power density above 2 GHz were normalized to the corresponding ICNIRP reference levels and then summed as follows:

$$I_{cum} = \sum_{i>30 \text{ MHz}}^{2 \text{ GHz}} \left(\frac{E_{max,i}}{E_{RL,i}} \right)^2 + \sum_{2 \text{ GHz}}^{300 \text{ GHz}} \left(\frac{S_{max,i}}{S_{RL,i}} \right)^2 \quad (1)$$

where $E_{max,i}$ and $S_{max,i}$ represent the maximum electric field strength and power density at frequency (i), respectively, and $E_{RL,i}$ and $S_{RL,i}$ are the corresponding ICNIRP reference levels. An I_{cum} value exceeding 1 indicates that the cumulative exposure exceeds the

guideline level. Therefore, in this review, cross-study comparisons are based primarily on the percentage of the applicable limit rather than on direct comparison of raw exposure quantities. For future multi-source exposure assessment, results expressed in terms of SAR, absorbed power density, incident power density, or field strength should first be converted into normalized exposure ratios according to the applicable frequency range and guideline quantity before cumulative indices are calculated.

In 2022, Tognola et al. [78] provided an earlier comprehensive survey of RF-EMF exposure in connected cars, covering V2X communications, automotive radar, and intra-vehicle wireless communication technologies over the frequency range of 100 MHz–200 GHz. Their review summarized the relevant technical characteristics, standards, deployment scenarios, exposure-assessment methods, source positions, exposure quantities, and main outcomes of the available studies. Therefore, the contribution of the present review is not to introduce the topic *de novo*, but to update and reorganize the evidence base within a more explicit exposure-assessment framework. Compared with that earlier review, the present study extends the literature search to March 2026 and incorporates more recent studies on 5G-V2X road-user exposure, child and adult anatomical models, real-vehicle and phantom-based measurements, sunroof-dependent V2V exposure, and 24/79 GHz automotive radar compliance assessments. In addition, this review distinguishes frequency-dependent exposure quantities, separating SAR-based assessments at or below 6 GHz from absorbed power density, incident power density, and temperature-rise assessments above 6 GHz. To improve cross-study comparability, the extracted variables include operating frequency, transmitted power, source location, exposed subject or model, exposure metric, peak exposure value, percentage of the applicable limit, main exposed body region, source-to-body distance where available, and vulnerable populations considered. Accordingly, Tables 3 and 4 summarize the quantitative exposure and compliance results for in-vehicle RF sources at or below 6 GHz and above 6 GHz, respectively, whereas Table 5 complements these tables by comparing exposure geometry and population-related characteristics.

4.1. Exposure Scenarios of V2X Communication Systems

Existing studies [60–63] consistently demonstrate that the electromagnetic exposure levels generated by V2X systems are significantly below the limits recommended by ICNIRP, indicating compliance with ICNIRP limits under typical operating conditions.

Schilling et al. [9] evaluated RF exposure from various wireless devices at nine representative locations inside a vehicle based on ICNIRP guidelines. Their results showed that the maximum radiation levels from ITS-G5 antennas (mounted on the windshield and roof), Bluetooth systems (external hands-free and integrated systems), and in-vehicle Wi-Fi systems were all below the ICNIRP reference levels.

In 2023, Benini et al. [60] assessed RF-EMF exposure in four child models of different ages and genders positioned at the front and rear of a vehicle (Figure 7a). Subsequently, in 2024, Benini et al. [61] further compared whole-body SAR values between child and adult human models exposed to 5.9 GHz V2V and V2I communications in urban environments, demonstrating that adults experienced higher exposure levels than children.

Yang et al. (2024) [62] conducted both numerical simulations and experimental measurements to evaluate RF exposure induced by a 5.9 GHz V2X system (including roadside units and onboard units), as well as wireless technologies integrated in a Tesla Model S (2.4 GHz Bluetooth, 1.8 GHz LTE modules, and mmWave radar), as illustrated in Figure 7b.

In 2025, Wang et al. [63] systematically investigated the electromagnetic exposure of a driver to a 5.9 GHz V2V antenna using the finite element method (FEM), calculating both SAR_{10g} and temperature rise after 30 min exposure (Figure 7c). Furthermore, in 2026, Song et al. [79] examined, for the first time, the impact of sunroof conditions (no sunroof, closed,

and open) on driver exposure during 5.9 GHz V2V communication. The results indicated that the open sunroof scenario represented the worst-case condition, with a peak skin SAR_{10g} of 72.39 mW/kg (3.62% of the safety limit), while the gray matter SAR_{10g} increased by a factor of 9.58 compared to the no-sunroof case. Nevertheless, all exposure metrics remained well below ICNIRP limits, indicating that the assessed driver exposure complied with current thermal-effect limits under the simulated 5.9 GHz V2V scenarios. This study fills a critical research gap regarding the influence of vehicle structural configurations on in-cabin electromagnetic exposure.

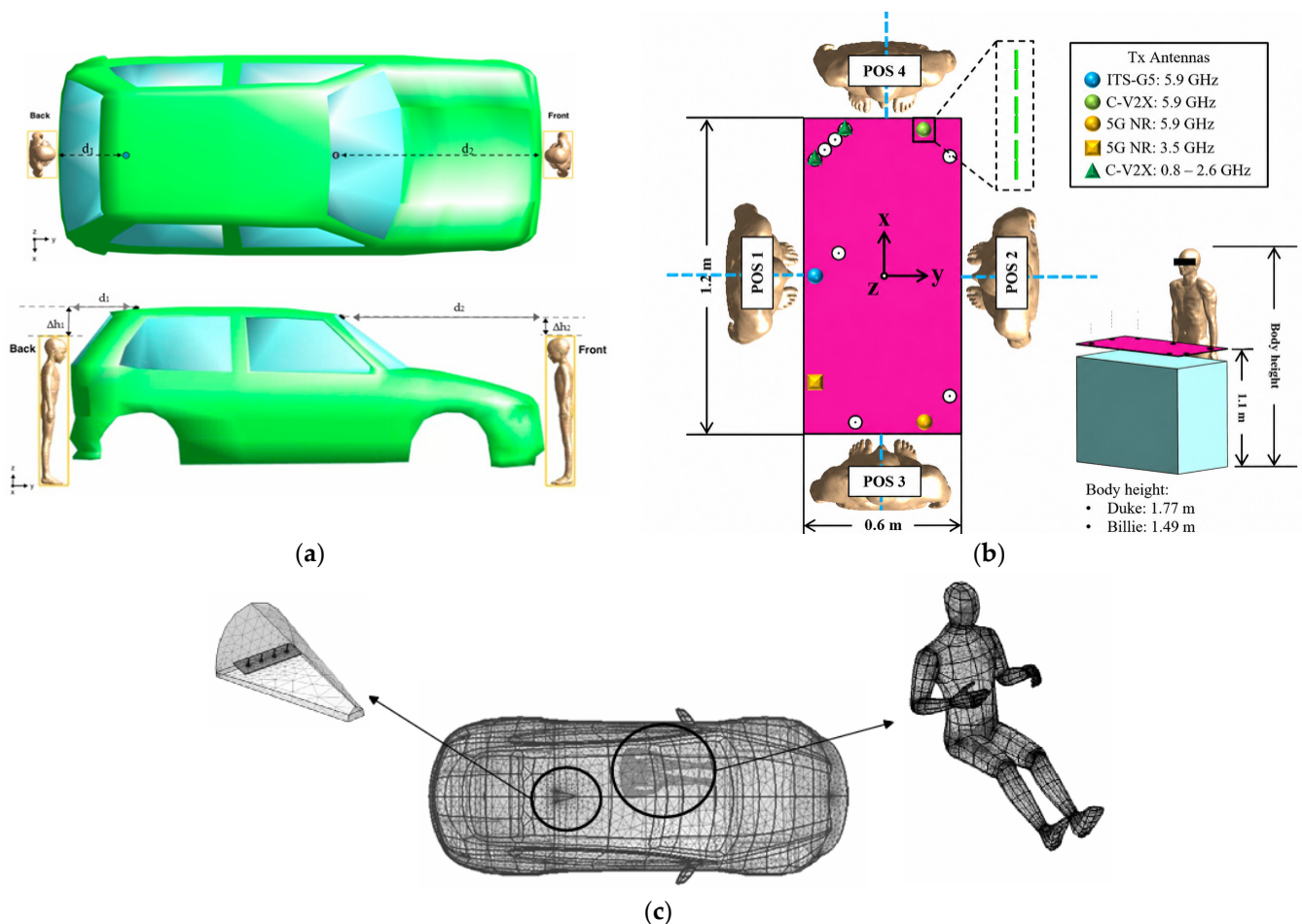


Figure 7. (a) RF-EMF exposure of child models at front and rear vehicle positions; (b) In-cabin exposure scenario under multi-band V2X antenna radiation; (c) Finite element model of an adult driver exposed to a V2V antenna.

For 5G-V2X systems operating at 3.5 GHz, an Italian research group conducted a series of detailed investigations [19,64]. In 2022, they employed the finite-difference time-domain (FDTD) method to evaluate RF exposure in pedestrians and other road users under various positions and postures, analyzing both SAR_{wb} and SAR_{10g} . The results indicated that the maximum SAR_{10g} occurred in the head region. In 2023, the same group applied the polynomial chaos Kriging (PC-Kriging) method to estimate stochastic spatial exposure distributions in 5G-V2X scenarios, revealing variations in exposure levels with different beam scanning angles in both E- and H-planes. In 2025, they further introduced ordinary Kriging (OK) and co-Kriging (Co-Kriging) interpolation techniques to estimate electric field distributions in urban V2X communication environments at 5.9 GHz [80], enabling efficient and low-complexity electromagnetic exposure prediction, wireless coverage estimation, and radio environment mapping.

Additionally, Struck et al. [81] proposed a novel real-time exposure assessment method for ITS-G5 V2X communication at 5.9 GHz, based on channel sniffing. By capturing and decoding V2X packets using commercial onboard units, the method calculates per-packet radiation energy and converts it into standardized electric field strength values. This approach enables accurate time–frequency domain exposure characterization in real traffic environments and provides a reliable measurement framework for future studies on electromagnetic exposure in vehicular networks.

4.2. Vehicular Radar Exposure Scenario

Vehicular radar systems primarily operate in the mmWave frequency bands of 24–29 GHz and 76–81 GHz [82]. Previous studies [66–69] have investigated electromagnetic exposure within these frequency ranges; however, they did not explicitly focus on radar-specific scenarios. Their findings were systematically summarized by Tognola et al. in [78].

At present, relatively limited research has been conducted on electromagnetic exposure in vehicular mmWave radar scenarios. As illustrated in Figure 8, Xie et al. [65] quantitatively evaluated the electromagnetic exposure safety of a 24 GHz collision-avoidance radar in electric vehicles using the finite element method. The maximum whole-body SAR (SAR_{wb}) and absorbed power density (S_{ab}) were observed for a human subject seated in the driver's position. For a single antenna mounted on the side of the vehicle, SAR_{wb} was 1.67×10^{-6} W/kg, and S_{ab} was 0.97 W/m². When two or four antennas were installed, SAR_{wb} increased to approximately ten times that of the single-antenna scenario. The results indicate that the electromagnetic exposure induced by 24 GHz automotive radar remains significantly below the limits specified by the International Commission on Non-Ionizing Radiation Protection (ICNIRP).

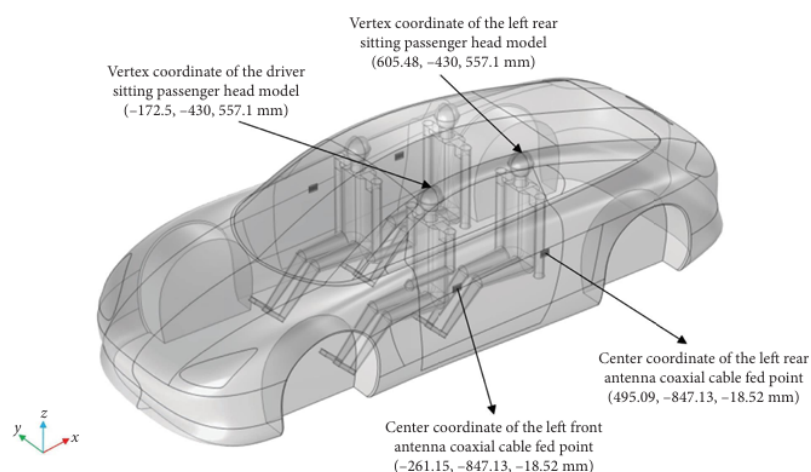


Figure 8. Exposure scenario of a 24 GHz automotive collision-avoidance radar in an electric vehicle.

Yang et al. [62] evaluated the electromagnetic exposure of a mmWave radar mounted on a Tesla Model S. Spectrum measurements revealed that the radar operated at 57.35 GHz and 58.45 GHz. At 20 cm from the radar, the maximum measured electric field strength was 10.48 V/m, corresponding to a peak power density of 0.29 W/m² and an average power density of 0.029 W/m². These exposure levels are substantially lower than the ICNIRP reference limit of 10 W/m² for frequencies above 6 GHz. The study further indicated that, in multi-source exposure scenarios of intelligent connected vehicles, mmWave radar contributes up to 79% of the cumulative exposure index for pedestrians, significantly exceeding contributions from other vehicular RF sources such as V2X communication and Bluetooth.

Regarding electromagnetic exposure assessment of 79 GHz automotive radar, Sugiyama et al. [83] were among the earliest to investigate this issue. They employed a 12×1 patch array antenna to represent a realistic vehicular radar system and numerically calculated the incident power density (IPD) and absorbed power density (APD), followed by a preliminary comparison with ICNIRP guidelines for frequencies above 6 GHz.

Building upon this work, Morimoto et al. [70] conducted a more comprehensive and systematic study on higher-frequency (79 GHz) vehicular radar exposure scenarios. Both simulations and experimental measurements were performed to evaluate pedestrian exposure to a 12×1 array antenna. The results showed that, under typical operating power (EIRP = 26.8 dBm), exposure remains far below the safety limits even at 10 mm. Although exposure may exceed limits at very close distances under high power conditions (EIRP = 55 dBm), compliance with short-term exposure limits can still be achieved when assessed using absorbed energy density, given that pedestrian exposure durations are typically on the order of a few seconds (e.g., within 0.5 s).

4.3. Exposure Scenario of Vehicular Wireless Communication Systems

Exposure scenarios in vehicular wireless communication systems include both passengers using personal wireless devices inside the vehicle and onboard wireless communication systems. The scenarios discussed in [78] are not limited exclusively to vehicular communication systems; therefore, this paper refines the focus specifically on in-vehicle wireless communication exposure scenarios. Table 3 supplements relevant studies and their key findings.

Studies [84–90] have investigated the specific absorption rate (SAR) of passengers using wireless communication devices within the electromagnetically shielded environment of a vehicle. These studies evaluated human electromagnetic absorption under such conditions and consistently demonstrated compliance with international electromagnetic exposure safety standards.

Research works [9,40,62,72–76,91] have analyzed the electric field distribution around vehicular wireless communication devices across commonly used frequency bands, including 900 MHz, 1800 MHz, 2.4 GHz, and 5G bands (3.3–5 GHz).

In 2009, Ruddle et al. [92] systematically evaluated the SAR of vehicle occupants at 900 MHz. A transmission line matrix (TLM) method was employed to model a mid-sized sedan, and SAR distributions were compared for an external roof-mounted monopole antenna and three types of internal dipole antennas under different occupancy configurations (1–4 passengers). The results showed that SAR values generated by in-vehicle transmitters at 1 W continuous-wave power were significantly below ICNIRP public exposure limits, with worst-case values not exceeding 8% of the limit. Additionally, the study revealed that the effect of occupant number and distribution on SAR is complex and non-monotonic.

In a follow-up study, Ruddle et al. [93] extended the exposure assessment to the 400 MHz–2.4 GHz range and investigated the safety mapping between average electric field strength in an empty vehicle and occupant SAR. It was found that, below 1 GHz, SAR compliance can be conservatively ensured using average electric field levels. However, at higher frequencies (1.8 GHz and 2.4 GHz), existing safety factors may be insufficient, and stricter reference levels are required due to resonant effects. Furthermore, multi-source coexistence scenarios (e.g., multiple mobile phones and walkie-talkies operating simultaneously) may lead to cumulative exposure approaching safety limits.

Unlike simulation-based studies, Gombarska et al. [72] conducted in situ measurements of electric field strength inside vehicles in urban environments across the 500 MHz–3300 MHz range, covering GSM, Bluetooth, and Wi-Fi bands. Three scenarios were compared: idle, Bluetooth active, and active voice call. The results indicated that electric field

strength increased by approximately one order of magnitude during calls, with peak values near the windows; however, all measurements remained well below ICNIRP limits. The study also emphasized the need to consider cumulative exposure and potential non-thermal effects during prolonged driving.

Rodrigues and Fontgalland [94] experimentally investigated electromagnetic field distributions in vehicles at 2.045 GHz under multi-source conditions (1–4 monopole antennas). The results showed that reflections from the metallic vehicle body create a resonant cavity effect, enhancing RF energy within the cabin. The maximum measured electric field strength reached 4.82 V/m under four-source operation, which is below the ICNIRP limit (61 V/m) but higher than that measured in free space, highlighting the importance of considering reflective environments in exposure assessment.

Reference [74] quantitatively evaluated human exposure to a 900 MHz radiation source by measuring electric field strength at various antenna placements (roof, trunk lid, and window) and seating positions inside and outside the vehicle. The maximum value, considering measurement uncertainty, was 32 V/m, which does not exceed ICNIRP limits.

Baramili et al. [40] investigated a multi-band planar antenna (600 MHz–5000 MHz) mounted on vehicle glass as an exposure source. The antenna was installed at multiple positions on the front and rear windshields to evaluate driver exposure. The results showed that the lowest electric field strength occurred at the lower rear windshield positions, while the highest exposure was observed on the driver-side front windshield. All measured values were below FCC limits, and installation on the lower rear windshield was recommended. Figure 9 further summarizes this type of exposure configuration, including the windshield-mounted 4G/5G multi-band vehicular antenna, candidate antenna installation positions, and the driver model used for exposure assessment.

In 2025, Zhou et al. [95] developed a dedicated SAR measurement system for intelligent connected vehicle scenarios and analyzed measurement uncertainties, providing important references for vehicular electromagnetic safety assessment. In 2026, Feng et al. [77] established a full-body seated human local SAR measurement system for realistic vehicular environments. Using a 4G TD-LTE mobile phone (200 mW, Bands 38/39/40) as the radiation source, they calibrated electric field probes using a three-antenna method and conducted in-vehicle measurements with tissue-equivalent liquids over 0.2–6 GHz. The results demonstrated that local SAR levels inside the vehicle are significantly below safety limits. Figure 10 illustrates the corresponding realistic in-vehicle exposure scenario, in which a seated occupant uses a mobile phone inside the passenger compartment. Earlier, in 2004, Heddebaut et al. [71] investigated the influence of passengers on WLAN antenna propagation within vehicles but did not analyze their interaction.

In addition to civilian vehicular communication systems, military vehicle antennas also constitute RF exposure scenarios. Colella et al. [96] investigated a high-frequency (HF, 16 MHz) vehicular monopole antenna by simulating a near-field exposure scenario in which an operator stands at a hatch with the upper body exposed outside the vehicle. The results showed that although local electric field strength in free space (127 V/m) exceeded the ICNIRP reference level (86.3 V/m), the whole-body SAR (0.2 mW/kg) and head SAR_{10g} (3.2–14.0 mW/kg) remained well below safety limits. When the operator wore a helmet and wired headset, local SAR near the ear increased slightly (up to approximately 40 mW/kg), but still satisfied safety requirements. This study demonstrates that even when external field strength exceeds reference levels, internal absorbed dose may remain within safe limits.

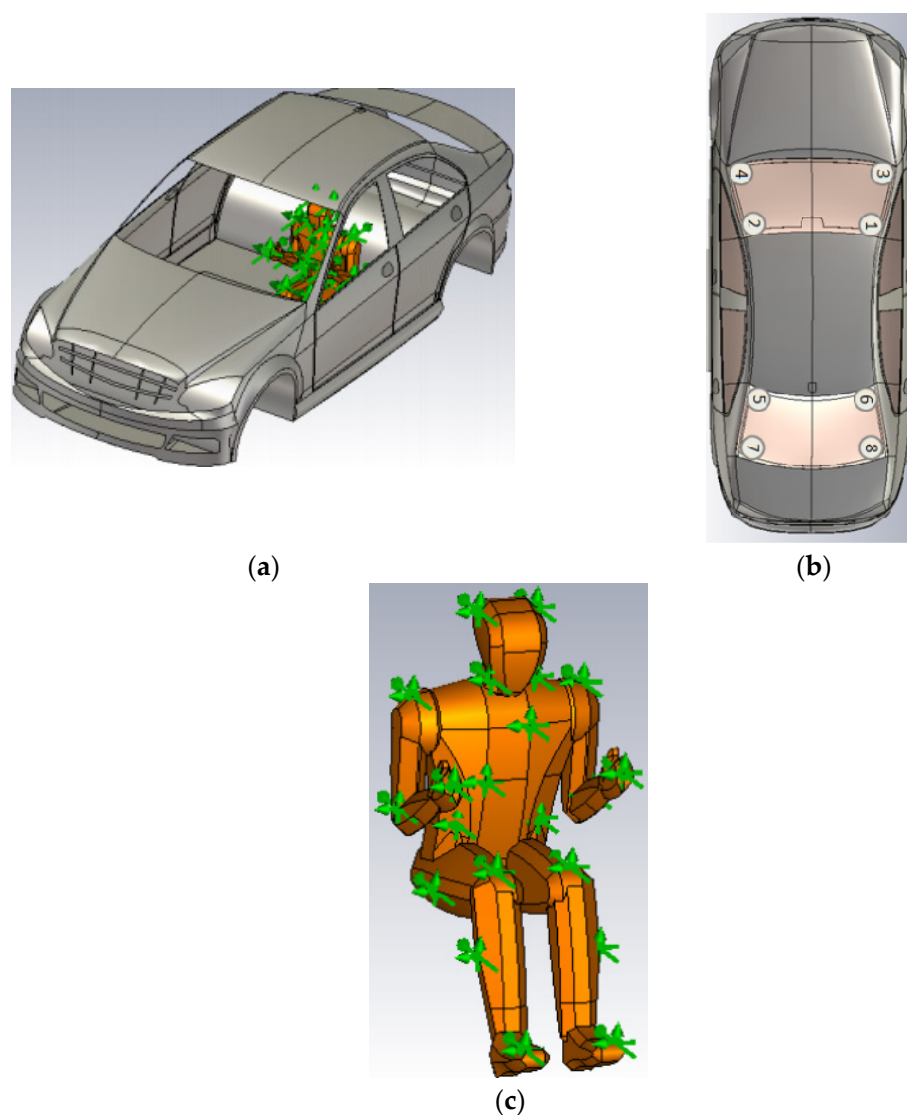


Figure 9. (a) Exposure scenario of a 4G/5G multi-band vehicular antenna mounted on the front or rear windshield, where the orange model represents the driver and the green markers indicate the electric-field probe locations; (b) Antenna installation positions, with positions 1–4 located on the front windshield and positions 5–8 located on the rear windshield; (c) Driver model.

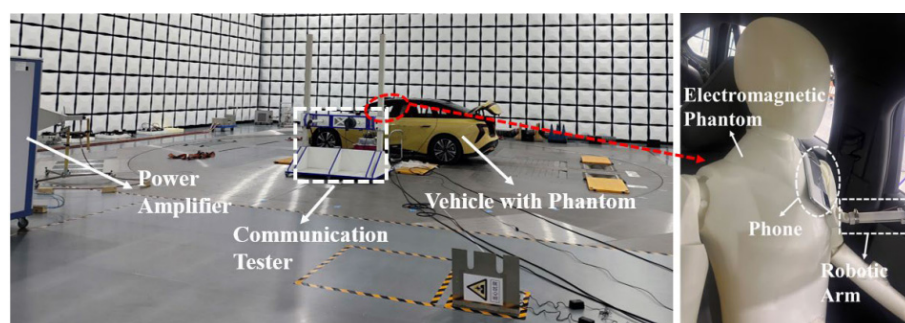


Figure 10. Realistic exposure scenario of in-vehicle occupants using a mobile phone.

Table 3. Summary of exposure-assessment studies for in-vehicle RF sources at or below 6 GHz.

Reference	Radiation Source	Frequency/Power	Method	Reference Standard	Peak Exposure, % of Limit, and Assessment
Schilling et al. (2022) [9]	ITS-G5, Wi-Fi, Bluetooth	ITS-G5: 5.9 GHz, EIRP 2 W; Wi-Fi: 2.4–5.725 GHz, 0.025–1 W; BT: 2.4 GHz, 0.1 W	Experimental measurement; Narda SRM-3006; duty-cycle correction	ICNIRP 1998 public reference level: 61 V/m	Max RMS E-field: ≈ 9.2 V/m, 15.1% of ICNIRP limit; all cases below reference level
Bonato et al. (2022) [19]	5G-V2X antennas	3.5 GHz; two antennas, 1 W each	Numerical simulation; FDTD in Sim4Life (ZMT Zurich Med Tech AG, Zurich, Switzerland; www.zurichmedtech.com , accessed on 18 July 2022)	ICNIRP public basic restrictions: SAR _{wb} 0.08 W/kg; head/torso SAR _{10g} 2 W/kg	Max SAR _{10g} : 6.818 mW/kg, 0.34% of limit; max SAR _{wb} : 0.074 mW/kg, 0.093%; all below limits
Bonato et al. (2023) [64]	5G-V2X antenna	3.5 GHz; 1 W	Numerical simulation; FDTD in Sim4Life; PC-Kriging stochastic dosimetry	ICNIRP public basic restrictions: SAR _{wb} 0.08 W/kg; head/torso SAR _{10g} 2 W/kg	Max SAR _{10g} : 9.54 mW/kg, 0.48% of limit; max SAR _{wb} : 0.33 mW/kg, 0.41%; all below limits
Benini et al. (2023) [60]	V2V/ITS 5.9 GHz vehicular connectivity	5.9 GHz; two antennas, 1 W each	Numerical simulation; FDTD in Sim4Life	ICNIRP/IEEE public basic restrictions: SAR _{wb} 0.08 W/kg; SAR _{10g} 2 W/kg for head/torso	Max SAR _{10g} : 9 mW/kg, 0.45% of 2 W/kg limit; max SAR _{wb} : 0.18 mW/kg, 0.225% of 0.08 W/kg limit; all below limits
Benini et al. (2024) [61]	V2V and V2I/ITS-G5 communication	5.9 GHz; 33 dBm each	Numerical simulation; raytracing in Wireless InSite; wbSAR estimation	ICNIRP/IEEE public basic restriction: SAR _{wb} 0.08 W/kg	Max SAR _{wb} : 4.9×10^{-4} W/kg, 0.61% of limit; all scenarios below limit
Yang et al. (2024) [62]	RSU/OBU V2X, Bluetooth, LTE	ITS-G5/C-V2X: 5.9 GHz, 23–33 dBm; Bluetooth: 2.4 GHz; LTE: 1.8/2.6 GHz	Numerical simulation + experimental measurement; FDTD in Sim4Life; Narda SRM3006 spectrum analyzer (Narda Safety Test Solutions GmbH, Pfullingen, Germany)	ICNIRP public reference/basic limits: 61 V/m; SAR _{10g} 2 W/kg; SAR _{wb} 0.08 W/kg	Max RSU RMS E-field: 5.8 V/m, 9.5% of 61 V/m; max 5.9-GHz SAR _{10g} : 264 mW/kg, 13.2% of 2 W/kg; all below limits
Wang and Lu (2025) [63]	V2V antennas	5.9 GHz; 33 dBm	Numerical simulation; FEM in COMSOL Multiphysics (v.6.2); EM-thermal coupling	ICNIRP occupational basic restrictions: SAR _{wb} 0.4 W/kg; head/torso SAR _{10g} 10 W/kg; core temperature rise 1 °C	Max head SAR _{10g} : 0.981 W/kg, 9.81% of limit; SAR _{wb} : 0.008728 W/kg, 2.18%; core temperature rise: 0.055 °C, 5.5%; below limits
Song and Lu (2026) [79]	V2V antenna	5.9 GHz; 30 W/44.8 dBm	Numerical simulation; FEM in COMSOL	ICNIRP 2020 public basic restrictions: SAR _{wb} 0.08 W/kg; SAR _{10g} 2 W/kg	Max SAR _{10g} : 72.39 mW/kg, 3.62% of limit; max SAR _{wb} : 0.318 mW/kg, 0.396%; all below limits

Table 3. Cont.

Reference	Radiation Source	Frequency/Power	Method	Reference Standard	Peak Exposure, % of Limit, and Assessment
Gombarska et al. (2019) [72]	GSM/Bluetooth devices	500 MHz–3.3 GHz; power not reported	Experimental measurement; BK Precision 2650A spectrum analyzer (B&K Precision Corporation, Yorba Linda, CA, USA)	Electric-field exposure limits; specific standard not specified	Peak E-field not numerically reported; field strength increased during phone call but remained below exposure limits
Ruddle (2009) [92]	on-board transmitters	900 MHz; normalized to 1 W CW radiated power	Numerical simulation; TLM	ICNIRP 1998/1999/519/EC public SAR limits: SAR _{wb} 80 mW/kg; head/trunk SAR _{10g} 2 W/kg; limb SAR _{10g} 4 W/kg	Max SAR _{10g} : 320 mW/kg in limbs, 8.0% of limit; max SAR _{wb} : 6.277 mW/kg, 7.85%; below limits
Ruddle et al. (2010) [93]	On-board transmitters	400 MHz, 900 MHz, 1.8 GHz, 2.4 GHz; normalized to 1 W CW	Numerical simulation; TLM/FIT	ICNIRP 1998/1999/519/EC public limits: SAR _{wb} 80 mW/kg; head/trunk SAR _{10g} 2 W/kg; limb SAR _{10g} 4 W/kg	900 MHz reported case: max head/trunk SAR _{10g} 172.1 mW/kg, 8.6%; max limb SAR _{10g} 146.6 mW/kg, 3.7%; max SAR _{wb} 5.794 mW/kg, 7.2%; 400 MHz, 1.8 GHz, and 2.4 GHz peak SAR values not separately reported; all below limits
Rodrigues and Fontgalland (2011) [94]	Mobile-phone monopole antennas	2.045 GHz; four monopoles, 500 mW each	Experimental measurement; log-periodic antenna and spectrum analyzer	ANATEL/ICNIRP public reference levels: E-field 61 V/m; power density 10 W/m ²	Max in-vehicle E-field: 4.82 V/m, 7.9%; max power density: 0.0616 W/m ² , 0.62%; below limits
Fang et al. (2026) [77]	4G TD-LTE mobile phone	Band 38: 2.57–2.62 GHz; Band 39: 1.88–1.92 GHz; Band 40: 2.30–2.40 GHz; ~200 mW	Experimental measurement; E-field probe	ICNIRP local SAR limit: 2 W/kg	Max local SAR: 0.1613 W/kg, 8.07% of limit; below limit
Colella et al. (2022) [96]	HF vehicular antenna	16 MHz; 25 W	Numerical simulation; FDTD in Sim4Life	IEEE/ICNIRP/EU limits: E-field RL 86.3 V/m; SAR _{wb} 0.4 W/kg; SAR _{10Avg} 10 W/kg	Free-space E-field peak: 127 V/m, 147% of RL; max SAR _{10Avg} : 13.97 mW/kg, 0.14%; max SAR _{wb} : 0.21 mW/kg, 0.053%; SAR below limits

Table 4. Summary of exposure-assessment studies for in-vehicle RF sources above 6 GHz.

Reference	Radiation Source	Frequency/Power	Method	Reference Standard	Peak Exposure, % of Limit, and Assessment
Yang et al. (2024) [62]	mmWave radar	Around 60 GHz; transmit power not reported	Experimental measurement; FSV-3030 spectrum analyzer with mmWave probe	ICNIRP public reference level: power density 10 W/m ²	Max power density: 0.29 W/m ² , 2.9% of 10 W/m ² ; below limit
Xie and Lu (2025) [65]	anticollision radar antenna	23.75–24.15 GHz; 0.1 W per antenna	Numerical simulation; FEM in COMSOL; EM-thermal coupling	ICNIRP basic restriction/reference level: S _{ab} 20 W/m ² ; local temperature rise 2 °C	Max S _{ab} : 2.7301 W/m ² , 13.65% of limit; max local temperature rise: 0.220 °C, 11%; below limits
Morimoto et al. (2025) [70]	Automotive mmWave radar	79 GHz; EIRP 26.8, 35.4, and 55 dBm	Numerical simulation + experimental measurement; FDTD in XFDTD	ICNIRP 2020/IEEE C95.1: IPD 50.74 W/m ² over 1 cm ² and 25.37 W/m ² over 4 cm ² ; APD 40 W/m ² over 1 cm ² and 20 W/m ² over 4 cm ²	26.8 dBm: IPD 10.3% and 13.6% of limits; 55 dBm: IPD 6760% and 10000% of limits; max APD exceeded limit by 22.4 dB; 35.4 dBm complied with all limits

Table 5. Source Location, Exposure Geometry, and Population Characteristics in Reviewed In-Vehicle RF Exposure Studies.

Reference	Radiation Source	Source Location	Exposed Position	Main Exposed Position/Body Region and Distance	Vulnerable Population Considered
Schilling et al. (2022) [9]	ITS-G5 antenna	Car roof or upper windscreen corner inside the driver’s cabin	Vehicle occupants	In front of the antenna; direct-contact probe measurement also performed, not a human-body distance	No
	Bluetooth devices	External hands-free antenna inside passenger cabin; integrated module near center control elements	Vehicle occupants	In front of the antenna or driver-seat footwell; exact source-to-body distance not reported	No
	Integrated Wi-Fi module	Near center control elements	Vehicle occupants	In front of the antenna; exact source-to-body distance not reported	No
Bonato et al. (2022) [19]	5G-V2X antennas	Windshield glass and rear rooftop	Pedestrian/road user; adult female model	Front, lateral, and rear positions around the car; minimum 1 mm from car body; head/eyes and right arm most exposed	Pedestrians; no children
Bonato et al. (2023) [64]	5G-V2X antenna	Windshield glass, along car midline	Adult pedestrian; Ella model	Near front hood, along car midline; antenna-to-body distance about 1.7 m	Pedestrians; no children
Benini et al. (2023) [60]	V2V antennas	Back roof and tilted windscreen	Child pedestrians	Front/back of car; nearest-antenna distance 539–547 mm at back and 1623–1625 mm at front; head/eyes most exposed	Children

Table 5. Cont.

Reference	Radiation Source	Source Location	Exposed Position	Main Exposed Position/Body Region and Distance	Vulnerable Population Considered
Benini et al. (2024) [61]	V2V antennas	Vehicle roof	Road users; adult and child models	Urban road-user positions; about 2–11 m from transmitting vehicles	Children
Yang et al. (2024) [62]	Bluetooth/LTE modules	In-cabin Bluetooth device; LTE antenna in rearview mirror housing	Driver and passenger	Driver/passenger torso; LTE measured at 0, 15, and 50 cm from rearview mirror housing	No
Wang and Lu (2025) [63]	V2V monopole array antenna	Rear roof, inside shark-fin shell	Driver; adult male model	Driver seat; upper body/head closer to antenna; exact distance not reported	No
Song and Lu (2026) [79]	V2V antenna	Rear roof, inside shark-fin antenna	Driver; adult male Duke model	Driver seat; exact source-to-body distance not reported	Eyes considered
Gombarska et al. (2019) [72]	Bluetooth and GSM sources	In-vehicle Bluetooth source; phone in dashboard compartment	Driver and passengers	Five front-seat points at chest height; exact source-to-body distance not reported	No
Ruddle (2009) [92]	900 MHz roof-mounted antenna	Rear roof	Driver and passengers; homogeneous adult male models	Driver, front passenger, and rear passengers; exact distance not reported	No
	900 MHz internal transmitters	Rear passenger compartment, between rear seats	Driver and passengers; homogeneous adult male models	Driver, front passenger, and rear passengers; exact distance not reported	No
Ruddle et al. (2010) [93]	On-board external transmitter	External vehicle-mounted monopole	Driver and passengers; adult male models	Driver, front passenger, and rear passengers; exact distance not reported	No
	On-board internal transmitters	Passenger compartment; rear/parcel-shelf/under-roof positions	Driver and passengers; adult male models	Driver, front passenger, and rear passengers; exact distance not reported	No
Rodrigues and Fontgalland (2011) [94]	2.045 GHz monopole antennas	One front passenger seat and three rear-seat positions	Vehicle occupants; adult-use scenario	Driver-position measurement; source-receiver distance about 0.81–1.20 m	No
Fang et al. (2026) [77]	Mobile phone	Inside vehicle, near phantom trunk	Vehicle occupant; seated full-body phantom	Trunk region; exact source-to-body distance not reported	No
Colella et al. (2022) [96]	HF vehicular monopole antenna	Vehicle roof, near turret manhole	Military operator; adult male Duke model	trunk/head near antenna; manhole about 50 cm from antenna	Military/occupational personnel; no children
Xie and Lu (2025) [65]	24 GHz anticollision radar antenna	Inside electric-vehicle side doors	Driver, passengers, and pedestrians; adult models	Passenger head positions, about 0.72 m from nearest antenna; pedestrian head positions, about 1.03 m from nearest antenna	Pedestrians; no children
Morimoto et al. (2025) [70]	Automotive mmWave radar	Behind vehicle emblem/front grille	Pedestrians; adult models	Thigh and eye/face near vehicle emblem; 10–116.4 mm from antenna	Pedestrians; eye exposure

5. Conclusions and Future Perspectives

This paper systematically reviews various types of vehicular high-frequency communication devices over the past decades, focusing on antenna design, operating frequency, and application scenarios, and provides a comprehensive analysis of their electromagnetic safety.

Vehicular wireless networking systems encompass multiple radio-frequency (RF) technologies, including V2X communication, 5G-V2X, GNSS positioning, mobile communication, Bluetooth, and automotive radar, covering a wide frequency range from 30 kHz to 300 GHz. Across the exposure scenarios assessed in the reviewed studies, most reported electromagnetic exposure levels from vehicular RF devices were below the applicable limits established by the International Commission on Non-Ionizing Radiation Protection (ICNIRP) or IEEE.

The following values are therefore presented as representative, study-specific findings rather than as directly pooled estimates, because the reviewed studies differ in source type, operating frequency, antenna configuration, exposure scenario, human model, and dosimetric endpoint. Specifically, for V2X communication systems operating at 5.9 GHz, the maximum localized SAR_{10g} in the driver's head under worst-case conditions is approximately 0.981 W/kg, corresponding to 9.81% of the ICNIRP occupational limit (10 W/kg). The whole-body SAR is 0.008728 W/kg, and the 30 min averaged core temperature rise is 0.055 °C, representing only 5.5% of the allowable limit (1 °C) [63]. When the sunroof is open, the maximum skin SAR_{10g} reaches 72.39 mW/kg, accounting for 3.62% of the limit [79]. Pedestrian exposure in children is significantly lower than that in adults, with a maximum whole-body SAR of approximately 4.9×10^{-4} W/kg [61]. For 5G-V2X systems at 3.5 GHz, the maximum head skin SAR_{10g} for pedestrians is 6.818 mW/kg, remaining well below safety limits [64].

GNSS/navigation antennas are not summarized as primary RF exposure sources because they normally operate as passive receiving devices; their relevance to vehicular electromagnetic environments is mainly associated with positioning reliability, antenna integration, and electromagnetic compatibility. In the case of automotive mmWave radar, the whole-body SAR in a 24 GHz single-antenna scenario is as low as 1.67×10^{-6} W/kg, while multi-antenna configurations (two or four antennas) increase SAR by approximately one order of magnitude ($\approx 1.67 \times 10^{-5}$ W/kg), still far below the limit of 0.4 W/kg [65]. For 57.35/58.45 GHz radar, the maximum measured power density at a distance of 20 cm is 0.29 W/m² [62]. For 79 GHz radar, even at a very short distance of 10 mm under typical operating power (EIRP = 26.8 dBm), exposure remains well below the limit. Only under extremely high power (55 dBm) and very close proximity may short-term exposure approach the limit; however, compliance is still ensured when evaluated using absorbed energy density within 0.5 s [70].

For mobile communication and Wi-Fi/Bluetooth devices, the peak electric field strength in typical in-vehicle scenarios is approximately 32 V/m, which is below the ICNIRP reference level (61 V/m) [74]. Under simultaneous operation of four sources, the maximum electric field strength is 4.82 V/m [94]. The maximum measured local SAR of a 4G TD-LTE mobile phone (200 mW) inside the vehicle is 0.1613 W/kg, significantly lower than the limit of 2 W/kg [77]. Furthermore, studies on military vehicle antennas operating in the HF band (16 MHz) indicate that even when the external electric field strength (127 V/m) exceeds the ICNIRP reference level (86.3 V/m), the internal whole-body SAR (0.2 mW/kg) and head SAR_{10g} (3.2–14.0 mW/kg) remain well below safety limits [96].

Taken together, these study-specific findings indicate that the reported exposure levels generally remained within the applicable ICNIRP or IEEE limits under the assessed thermal-effect endpoints and operating conditions. However, this conclusion should not

be interpreted as evidence that all real-world vehicular RF exposure scenarios have been fully characterized.

These quantitative findings have scientific and engineering value, but their interpretation should remain linked to the specific assumptions and endpoints of each study. From a health-risk assessment perspective, the reviewed results provide evidence that, under the assessed scenarios, localized SAR, whole-body SAR, power density, and temperature rise were generally below the corresponding thermal-effect limits. For example, even under relatively conservative conditions, such as close proximity to antennas, multi-source operation, or sunroof-open scenarios, the reported maximum localized SAR did not exceed 49% of the ICNIRP limit, while core temperature rise remained below 6% of the allowable threshold. In several scenarios, including 24 GHz radar and 5G-V2X, reported exposure levels were two to four orders of magnitude lower than the relevant limits.

From an engineering design perspective, these quantitative results provide practical boundary conditions for vehicle manufacturers and antenna engineers. For instance, 79 GHz radar remains compliant even at a 10 mm distance under typical power levels, while multi-antenna configurations at 24 GHz increase SAR by only one order of magnitude. Such findings can guide antenna placement optimization and transmission power control strategies.

Furthermore, certain extreme scenarios—such as increased SAR under sunroof-open conditions or near-field exposure to high-power mmWave radar—highlight the necessity for cautious design under boundary conditions and provide insights for future refinement of safety standards. Rather than forming a unified dataset, the compiled evidence provides a comparative evidence map across different source types, frequency bands, exposure metrics, and assessment methods. This evidence map can help identify representative exposure ranges, methodological gaps, and priorities for future guideline refinement and risk assessment in vulnerable populations, including individuals with implants and pregnant women.

The strength of evidence also varies across studies. Higher-confidence evidence comes from studies that clearly report source parameters, antenna location, transmitted power, human model or measurement position, frequency-appropriate exposure metrics, validation procedures, uncertainty analysis, and explicit comparison with ICNIRP or IEEE limits. Lower-confidence evidence generally arises from simplified source models, incomplete reporting of exposure conditions, single-source assumptions, limited validation, or the absence of uncertainty quantification. This distinction should be considered when interpreting the reported values and when using them to inform exposure assessment or engineering design.

Despite extensive research efforts, several challenges and research gaps remain in the context of intelligent and autonomous vehicles:

- (i) Insufficient investigation of multi-source and multi-frequency composite exposure scenarios. Most existing studies focus on single-frequency or single-source exposure, whereas real vehicular environments involve simultaneous operation of multiple RF systems (e.g., V2X, 5G-V2X, GNSS, Bluetooth/Wi-Fi, and radar). Future studies should develop comprehensive multi-physics and multi-source exposure assessment frameworks. For such scenarios, cumulative exposure should be evaluated using normalized exposure ratios or cumulative indices rather than by directly comparing incompatible quantities such as SAR, field strength, and power density.
- (ii) Limited research on electromagnetic exposure in special populations. There is a lack of data for infants, children in car seats, implant users (e.g., pacemakers, cochlear implants), and pregnant women. In particular, interactions between RF systems and active medical implants remain largely unexplored.

- (iii) Oversimplified exposure scenarios. Most simulations assume static human models and single RF sources, neglecting real-world factors such as multiple devices, dynamic transmission power, multipath reflections, passenger posture, and vehicle configuration. In addition, recent studies on mmWave vehicular edge computing and fluid-antenna-assisted MEC networks indicate that future IoV systems may dynamically adjust transmit power, beam direction, resource allocation, and computation-offloading decisions according to channel conditions and service requirements [26,27].
- (iv) Lack of full-vehicle experimental validation and standardized evaluation methods. Current studies are dominated by simulations, with limited experimental validation. Differences in models, metrics, and scenarios hinder cross-study comparability, and standardized guidelines for vehicular RF exposure assessment are still lacking.
- (v) Insufficient research on long-term exposure and non-thermal effects. Existing assessments are primarily based on short-term thermal effects (SAR, power density, temperature rise), while long-term, low-level exposure and potential non-thermal biological effects remain largely unexplored.
- (vi) Lack of prospective assessment for emerging technologies. Future technologies such as 6G, terahertz communication, ultra-massive MIMO, and reconfigurable intelligent surfaces may introduce higher-frequency and higher-density RF exposure, requiring forward-looking safety evaluations.
- (vii) Limited biofidelity of human models. Current models do not adequately capture variability across age, gender, body composition, and anatomical differences, nor do they accurately represent implanted medical devices. High-fidelity modeling and uncertainty quantification are urgently needed.

In conclusion, this study provides a systematic review and quantitative analysis of electromagnetic exposure in vehicular RF systems, offering a solid theoretical foundation and reference framework for future safety standards and health risk assessments for both vehicle occupants and pedestrians.

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