→ THE EUROPEAN SPACE AGENCY

CONVERGING EARTH AND SPACE: ADVANCING AUTOMOTIVE CONNECTIVITY

By ESA CSC (Connectivity and Secure Communications)
Space for 5G/6G and Sustainable Connectivity

July 2025

Editors: Ivalina Petrova, Antonio Franchi

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1. EXECUTIVE SUMMARY

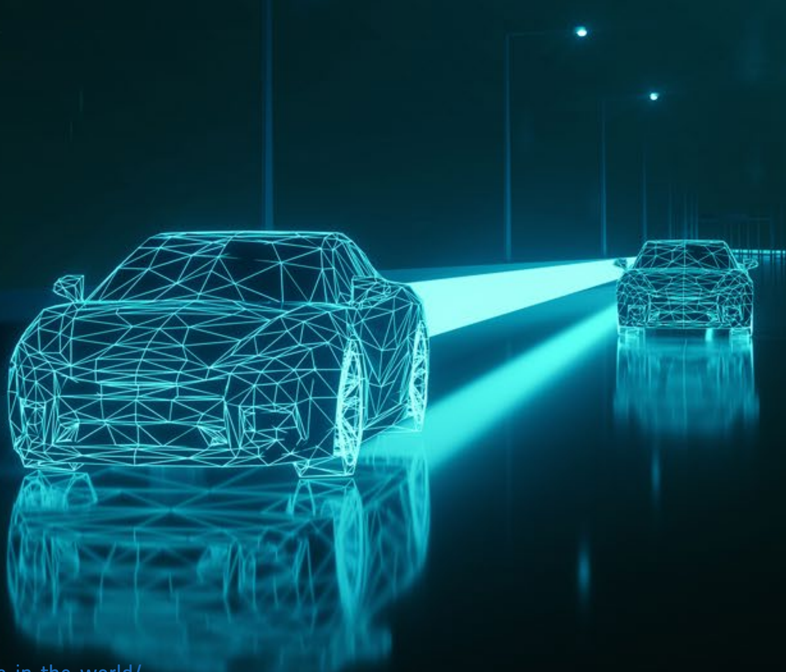
In the face of rapid technological evolution, traditional automotive business models are being disrupted, demanding new approaches to competitiveness in the global market. The European Space Agency's Directorate of Connectivity and Secure Communications and its Space for 5G/6G Programme Office are at the forefront of driving this transformation, collaborating with leading automotive partners to revolutionise mobility through space-based technologies. By fostering innovation in connected and autonomous vehicles, the European Space Agency (ESA) is unlocking new possibilities in smart transportation, laying the foundation for the future of mobility that integrates vehicles, infrastructure, and users in a seamless communication network.

The rapid evolution of low earth orbit (LEO) satellite constellations is transforming how industries approach communication. Unlike traditional communication models that rely on geostationary satellites, LEO satellites offer more agile, cost-effective, and scalable solution which when combined with increased mobility, perfectly align with the growing demands of connected vehicles. The automotive industry is now looking to LEO non-terrestrial networks as the connectivity solution to coverage gaps, along with enabling technologies such as direct-to-device, responding to the evolving needs of consumers and industries alike. By offering uninterrupted coverage and the ability to link remote regions where traditional terrestrial networks fall short, satellite technology is enhancing the scope of connected vehicle applications that range from in-vehicle services to smart city infrastructure integration. This transformation is a great opportunity not only for European automakers but also for the wider mobility ecosystem, providing a pathway to more sustainable, efficient, and scalable transport systems. With millions of vehicles recorded on the road[1], it is also of great importance to create road-safety infrastructure to ensure Vehicle-to-Everything (V2X) communications, improving traffic management, emergency response and mitigate accidents.

Europe stands in a strong position to foster the global transition to space-enhanced mobility solutions. The automotive and space industries in Europe must continue being at the cutting edge of their respective fields, and their collaboration is becoming essential. This convergence of space and automotive expertise is particularly crucial for Europe to solidify its industrial leadership and capitalise on the exponential growth of both sectors. Through such partnerships, Europe can unlock a future where satellite and terrestrial networks are harmonised, creating robust, hybrid connectivity solutions.

This white paper outlines the technological advancements and challenges towards connected mobility and the strategic importance of fostering collaboration between the automotive and space industries to harness the full potential of satellite-enabled systems. Drawing on insights from recent studies and reports, including those on satellite direct-to-device services and the integration of satellite with 5G technologies, there is an emphasised need for robust partnerships that can bridge the technological, regulatory, and operational challenges that remain.

Only by leveraging Europe's strengths in both sectors and embracing the transformative power of hybrid connectivity it would be possible to deliver on the promise of space-enabled mobility and ensure a more connected future for all.

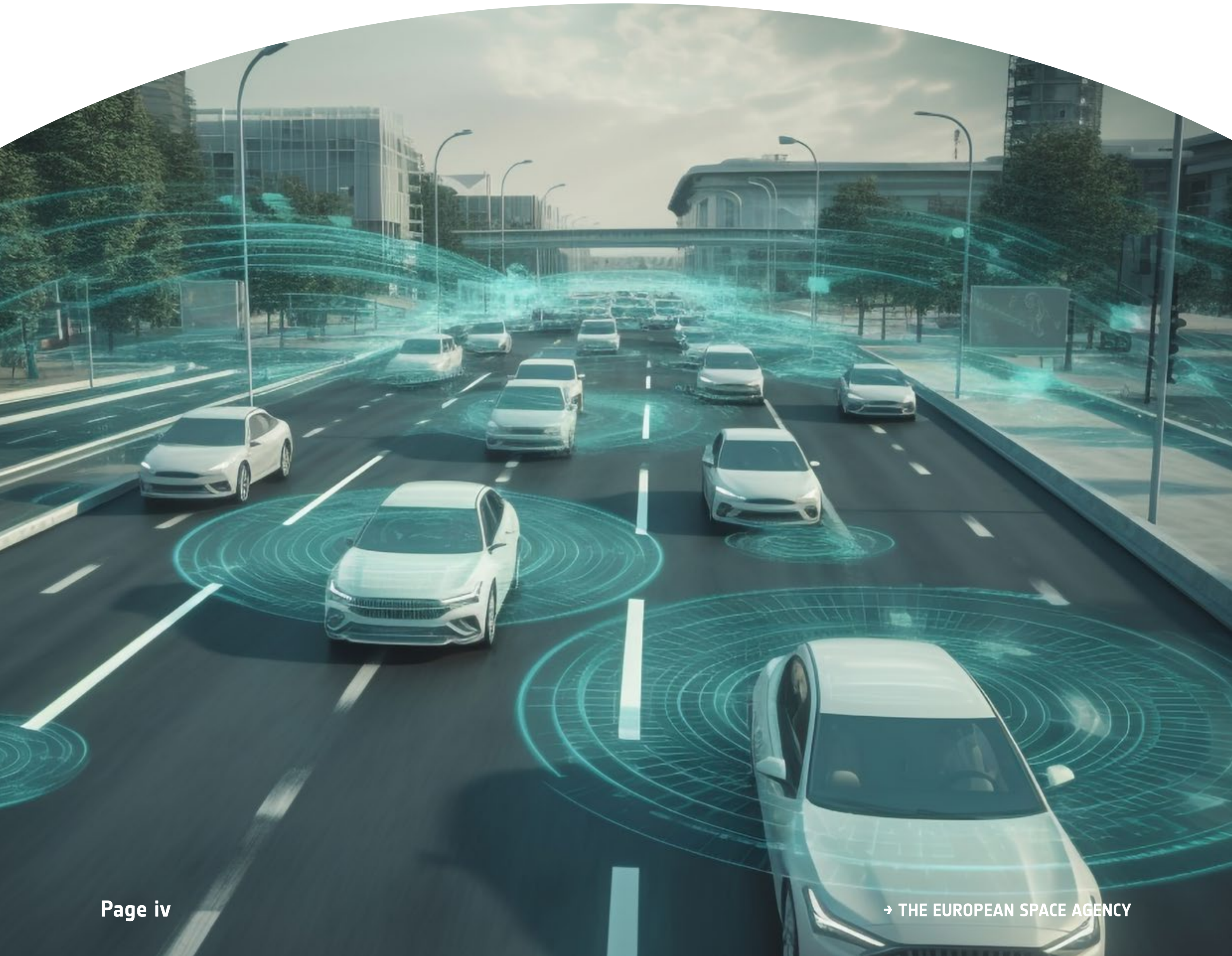


1 https://hedgescompany.com/blog/2021/06/how-many-cars-are-there-in-the-world/

LIST OF ABBREVIATIONS

Acronym	Definition
AC	Automotive Cloud
AD	Autonomous Driving
AI	Artificial Intelligence
ARTES	Advanced Research in Telecommunications Systems
AST	Advanced Space Technologies
AT&T	American Telephone and Telegraph Company
ATIS	Alliance for Telecommunications Industry Solutions
BMW	Bayerische Motoren Werke
CSC	Connectivity and Secure Communications
C-V2X	Cellular Vehicle-to-Everything
DARWIN	Demonstration and Research of Autonomous Vehicles using Intelligent systems
DLR	German Aerospace Center
DSRC	Dedicated Short-Range Communications
D2D	Direct-to-Device
D2V	Direct-to-Vehicle
EO	Earth Observation
ESA	European Space Agency
ETSI	European Telecommunication Standards Institute
ETSI TC ITS	ETSI Technical Committee on Intelligent Transport Systems
EV	Electric Vehicle
FCC	Federal Communications Commission
FR2	Frequency Range 2
GEO	Geostationary Orbit
GNSS	Global Navigation Satellite System
GSMA	Global System for Mobile Communications Association
IEEE	Institute of Electrical and Electronics Engineers
HD	High Definition
IoT	Internet of Things
ISAR	Integrated Satellite and Aerial Relay
ISL	Inter-Satellite Links
LEO	Low Earth Orbit
LiDAR	Light Detection and Ranging
MaaS	Mobility-as-a-Service
MEC	Mobile Edge Computing
MIMO	Multiple-Input Multiple-Output
mMTC	Massive Machine-Type Communication
MNO	Mobile Network Operator
MoU	Memorandum of Understanding
NB-IoT	Narrowband Internet of Things
NR	New Radio
NTHO	Non-Terrestrial Handover
NTN	Non-Terrestrial Network
OEM	Original Equipment Manufacturer
OHB	Orbitale Hochtechnologie Bremen
OTA	Over-the-Air
PC5	Proximity Communication Interface
RF	Radio Frequency
SDR	Software-Defined Radio
SDV	Software-Defined Vehicles
T-Mobile	Telekom Mobile
TN	Terrestrial Network

Acronym	Definition
UBI	Usage-Based Insurance
UE	User Equipment
URLLC	Ultra-Reliable Low-Latency Communications
V2I	Vehicle-to-Infrastructure
V2N	Vehicle-to-Network
V2V	Vehicle-to-Vehicle
V2X	Vehicle-to-Everything
3GPP	3rd Generation Partnership Project
5GAA	5G Automotive Association



2. ADVANCEMENTS IN SPACE FOR CONNECTED MOBILITY

2.1 THE FUTURE SMART CARS ARE BECOMING THE PRESENT REALITY

Smart cars are no longer a distant vision of the future – they are already here, equipped with advanced connectivity features that enhance safety, efficiency, and convenience. Many modern vehicles come with over 50 connectivity functions, allowing them to communicate with drivers, other cars, and infrastructure in real time, some of which are illustrated below. These vehicles function as advanced information hubs, offering a wide array of benefits that extend far beyond traditional navigation and entertainment systems. In fact, there is a major movement towards self-driving autonomous vehicles.

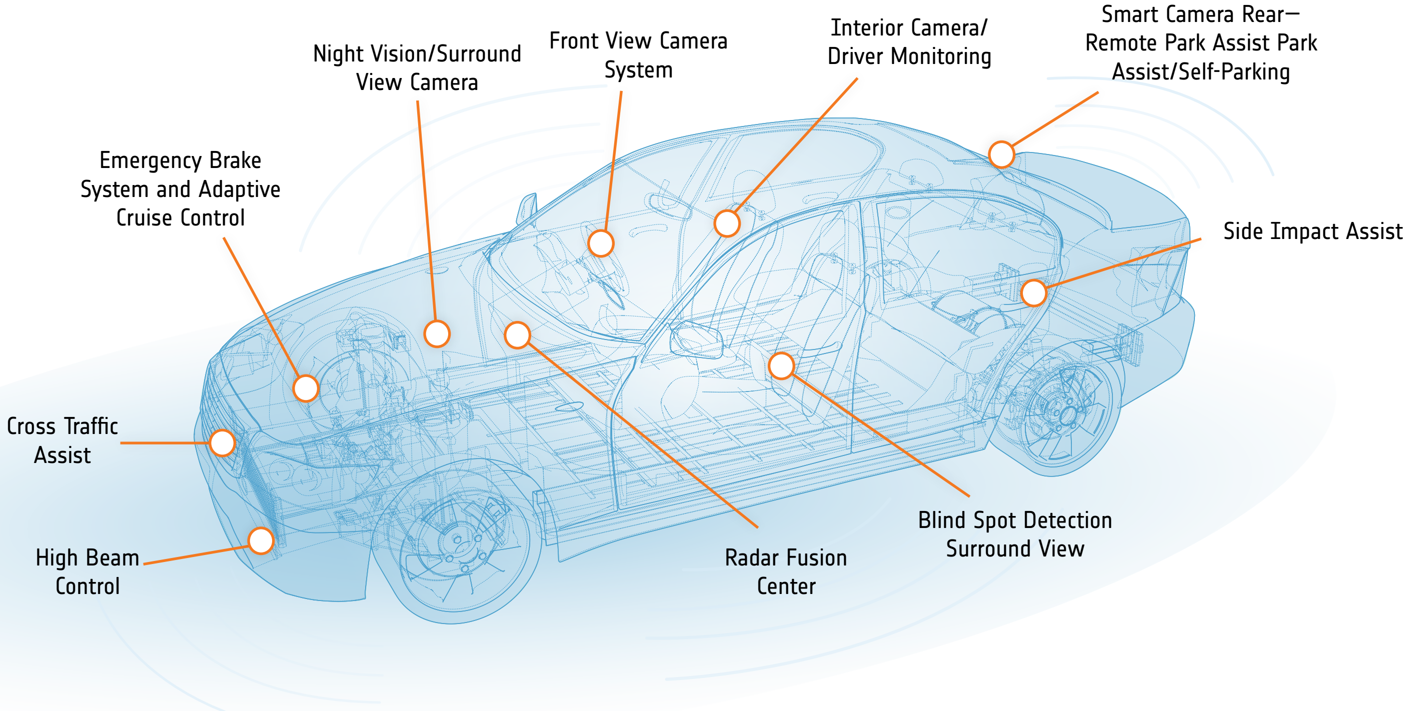


Figure 1: *Connectivity features of smart and autonomous vehicles.*
Source: Stephen Shankland—Freescale vision chip makes self-driving cars a bit more ordinary. Article, 2014.

As a result, major car manufacturers are now developing satellite connectivity strategies to cater for the need of service in areas out of coverage. For example, Tesla's strategy centres on a connected vehicle ecosystem with over-the-air updates and data collection to boost performance and safety. They plan to integrate Starlink connectivity, initially enabling emergency text and call features using Gen 2 satellites[2] Starlink has also developed enhance mobility antennas for optimized satellite-to-vehicle connection[3]. Another leading case study in this field is Geely, which has taken an active role in satellite deployment.

2 Euroconsult Prospects for Direct to Handheld and IoT Markets 2024.
3 Space News "New Starlink dish kit enables services on any moving land object"

The Chinese automaker launched its first set of low earth orbit (LEO) satellites in 2022 and has since expanded its constellation further with the launch of an additional 11 satellites. This expansion enhances Geely's ability to provide high-precision navigation and communication for autonomous vehicles. The company has ambitious plans to deploy 72 satellites by end of 2025, with a long-term goal of establishing a constellation of 240 satellites[4]. American multinational automobile manufacturer Ford is embracing this convergence by partnering with telecommunications company AT&T to bolster vehicle connectivity through cellular and 5G, while recognising the importance of satellite connectivity for expanding navigation, entertainment, and diagnostics service[5]. Meanwhile South Korea's Hyundai is strengthening its connected car ecosystem with a connected car Operating System (OS) that enables over-the-air updates and personalised services, such as the Hyundai Digital Key that transforms the user's smartphone into a key for their vehicle[6]. Additionally, their collaboration with a recognised graphics processing unit manufacturer NVIDIA enhances infotainment and performance while ensuring vehicles can leverage both satellite and ground-based networks for seamless connectivity[7]. Volkswagen is increasing the availability of their services by leveraging satellite technology integrated with terrestrial networks. Their partnership with Microsoft is driving the Automotive Cloud (AC) for vehicle data management[8], while their collaboration with ISAR Aerospace, which is responsible for launching satellites produced by EightyLEO, focuses on satellite-based internet for their vehicles, reflecting their commitment to a hybrid connectivity model[9]. Toyota is reinforcing this shift by investing in satellite technology to enhance navigation and autonomous driving. At the same time, their partnerships with telecommunications companies such as American Telephone and Telegraph Company (AT&T), Nippon Telegraph and Telephone Corporation (NTT), and Kokusai Denshin Denwa International (KDDI) ensure stronger in-vehicle connectivity services, further demonstrating the industry-wide move toward an integrated satellite-terrestrial ecosystem[10].

This collective push highlights a pivotal transformation in the automotive sector, where satellite and terrestrial networks are no longer separate but rather complementary forces driving the future of mobility. In response to this growing demand, European OEMs have also explicitly expressed their support for C-V2X direct communications to pave the way towards automated driving[11].

4 https://zgh.com/media-center/news/2024-09-03/?lang=en
5 https://about.att.com/story/2021/ford-manufacturing-facility.html
6 https://www.hyundai.news/eu/articles/stories/a-connected-car-experience-enabled-by-digital-services.html
7 https://www.hyundai.news/uk/articles/press-releases/hyundai-motor-group-partners-with-nvidia.html
8 https://www.volkswagen-newsroom.com/en/press-releases/volkswagen-and-microsoft-announce-strategic-partnership-4234
9 https://orbitaltoday.com/2021/03/12/volkswagen-partners-with-isar-aerospace-for-its-new-project/
10 https://about.att.com/story/2019/toyota_and_lexus.html
11 5GAA White Paper "A visionary roadmap for advanced driving use cases, connectivity, and technologies".

2.2 SPACE CONNECTIVITY FOR SAFETY ON THE ROAD

The idea for the connected car is not new. It was introduced as early as 2004, seeking to improve road safety and reduce accidents. Today, the need for a robust road safety solution is becoming critical. Research showed that 11% of total fatalities occurred on rural roads that remain unconnected[12].

The automotive industry's future lies not only in creating innovative vehicle functionalities but also in commercialising value-added safety services throughout the vehicle's lifecycle. Satellite-based solutions enable the digitalisation of vehicle platforms, allowing for continuous improvements in safety and driver experience, as well as incident mitigation.

Initially, vehicle communication relied on Dedicated Short-Range Communications (DSRC), standardized under IEEE 802.11p, for short-range connectivity.[13]

However, 3GPP introduced Cellular Vehicle-to-Everything (C-V2X) back in Release 14[14], enabling cellular-based communication that continues to evolve in later releases. A key advancement in C-V2X is the side link (PC5) interface, which allows direct, low-latency message exchanges between vehicles (V2V) and infrastructure (V2I).

While there is ongoing debate over the adoption of C-V2X versus DSRC, industry trends and technological advancements increasingly support C-V2X as the preferred solution for connected and autonomous mobility[3]. This solution is central to the rise of autonomous and electric vehicles (EVs), as it provides the robust and secure communication infrastructure necessary to support Vehicle-to-Vehicle (V2V) and Vehicle-to-Infrastructure (V2I) interactions. The term Vehicle-to-Everything (V2X) is used to denote all types of vehicle communications, irrespective of the technologies used to achieve it, as shown in Figure 2.

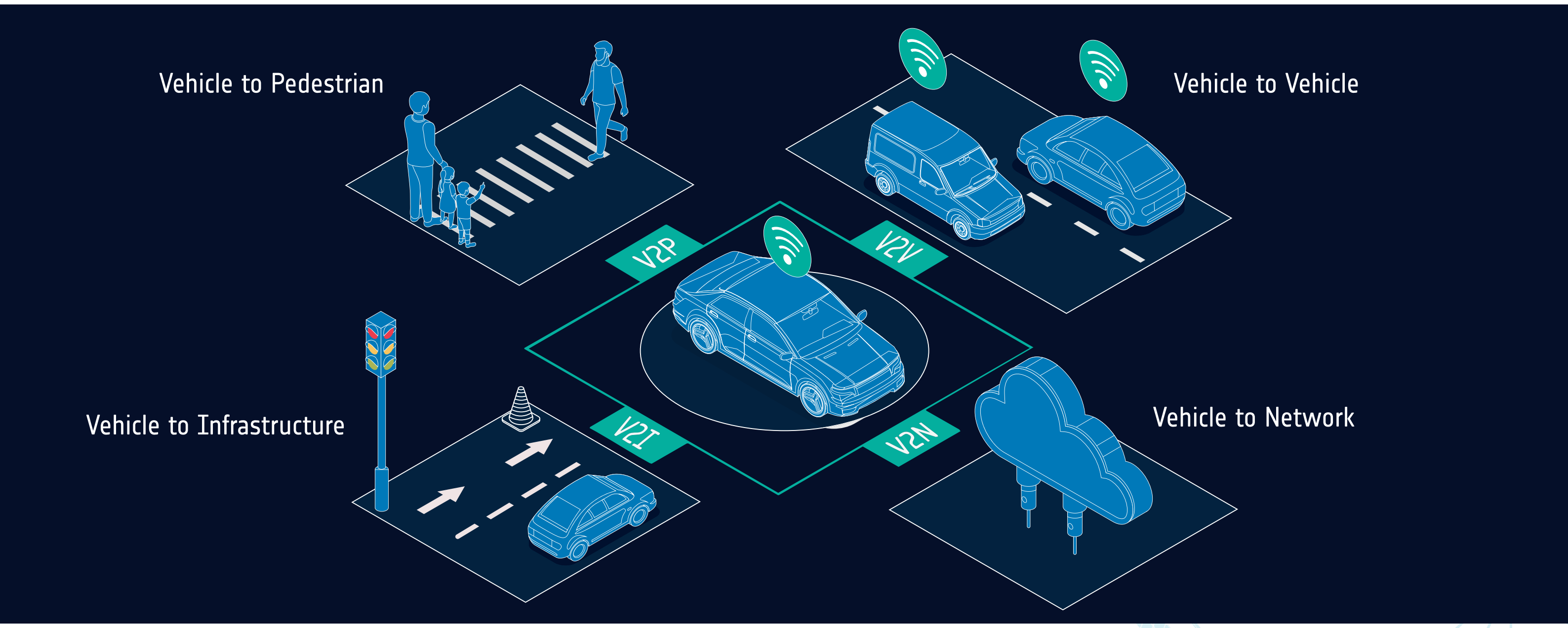


Figure 2: *V2X connectivity.*

12 Euroconsult Prospects for Direct to Handheld and IoT Markets 2024
13 IEEE 802.11p
14 https://www.3gpp.org/ftp/Specs/archive/22_series/22.885/

In a paper published by Einstein Ventures[15] the highlighted V2X functionalities address security on the road by highlighting roadwork and forward collision warnings, as well as real time steering of traffic to avoid bottlenecks and traffic jams based on street conditions. Those and many other applications towards road safety are heavily satellite communications dependent.

Satellite-enhanced V2X also grants law enforcement and traffic authorities real-time visibility into road conditions, enabling functions from proactive collision alerts to congestion management. Fine and Penalty Offices benefit by issuing penalties with greater accuracy and contextual justification. At a policy level, both national and EU regulators can refine transportation strategies by leveraging data generated through satellite-enabled V2X frameworks[16]. The insurance industry is also positioned for transformation. By accessing real-time V2X data, insurers can develop dynamic policies tailored to actual vehicle behaviour, improving both relevance and fairness. Similarly, the education sector, especially driving schools, can update curricula to include training in environments where vehicles continuously interact with their surroundings, enhancing unexperienced drivers' road awareness.

A lot of work on road safety is being done by the 5G Automotive Association (5GAA) who have now published the third edition of the C-V2X Roadmap[17] The work provides an update of 5GAA's vision for the global deployment of smarter, safer and more sustainable mobility and transportation services. It includes advanced driving use cases and offers a road operator perspective on their deployment with a particular focus on safety in the EU regions and on the role of 5G. This is exemplified by AT&T's partnership with General Motors[18] and the satellite communications solution provider Viasat's membership in the 5G Automotive Association (5GAA) to advance autonomous transportation systems.[19]

The adoption of 5G connectivity solutions is becoming even more relevant with the number of connected vehicles on the road reaching more than 350 million globally[20]. With an estimated 2.5 billion connected cars anticipated worldwide by 2030 and a projected 20-fold increase in data consumption per vehicle, rural connectivity will play a pivotal role in shaping the smart vehicle landscape and ensuring road safety. Recent research found that 10% of driving time was spent out terrestrial network coverage across 14.4 million registered trucks and 5% of driving time for 285 million registered cars.[6] Thereafter, the coverage gaps must be addressed. Cellular vehicle-to-everything communications have enabled connected car services, but their evolution towards satellite communications is critical for this connectivity solution's ubiquity.

ESA's vision of future of connected mobility is built on the premise that connectivity will drive sustainable and safe practices and offer new business models for the automotive sector, promising access to remote diagnostics, over-the-air software updates, and real-time fleet management for both autonomous and electric vehicles through the development satellite-enabled V2X communications. These capabilities not only ensure the safe and continuous operation of connected cars but also reduce resource consumption by providing users with insights that optimise energy usage and enhance operational efficiency.

15 https://www.einstein-iv.space/space-enabled-applications-in-the-automotive-sector
16 https://www.einstein-iv.space/space-enabled-applications-in-the-automotive-sector
17 5GAA White Paper "A visionary roadmap for advanced driving use cases, connectivity, and technologies"
18 https://about.att.com/story/2021/att_gm_5g.html
19 https://news.viasat.com/newsroom/press-releases/viasat-joins-5g-automotive-association-to-support-satellite-enabled-autonomous-vehicles-and-predictive-safety
20 Euroconsult Prospects for Direct to Handheld and IoT Markets 2023.

3. CONNECTIVITY PARTNERSHIPS

3.1 INNOVATION TROUGH COLLABORATION

The European Space Agency (ESA) plays a pivotal role in fostering collaboration between the space and automotive industries to establish a hybrid space-ground connectivity ecosystem for connected and autonomous vehicles. By leveraging non-terrestrial network solutions, ESA aims to maintain Europe's competitiveness in the global automotive industry while ensuring digital sovereignty and leadership in next-generation mobility solutions. A strong partnership between vehicle manufacturers, digital service providers, and the space industry is essential to achieving a state-of-the-art European solution for connected cars, at least by the end of this decade. This effort supports innovation, regulatory compliance, and superior digital services, positioning Europe at the forefront of the expanded value chain in the global automotive market. The space industry, in turn, benefits by offering new services in this emerging sector, strengthening Europe's technological and economic influence.

ESA is actively driving discussions with industry leaders and policymakers to shape the future of space-enabled vehicle connectivity. Through demonstrations, trials, and proof-of-concept implementations, ESA supports the integration of satellite-based communications with terrestrial 5G and future 6G networks aiming at increase of availability, seamless coverage and low-latency connectivity.

The DARWIN project, of Darwin Innovation Group on the Harwell Science and Innovation Campus in the UK, serves as a successful example of this approach, with trials demonstrating 99% connectivity availability, meeting the critical session continuity requirements necessary for a seamless user experience. This DARWIN collaboration resulted in a successful autonomous shuttle currently in continuous operation around Harwell Campus[21].

ESA's support extends beyond technical development to business enablement, providing co-financing schemes, formulating strategic partnerships, and defining optimal cost-sharing models between onboard vehicle technology, ground-based infrastructure, and satellite constellations. The Agency's Advanced Research in Telecommunications Systems (ARTES) programme plays a crucial role, offering a commercially driven and flexible funding framework. With contributions from ESA Member States, the programme helps manage risks while supporting businesses in achieving their strategic objectives. Funding support ranges from 50% to 80%, and for universities and research institutions, it can reach 100%, ensuring strong backing for technological and commercial advancements. Furthermore, ESA ensures that all intellectual property rights remain with the industry, enabling full freedom in determining consortium size, diversity, and collaboration models.

ESA has also built a long-standing collaboration with 5GAA, strengthening the connection between the automotive and space ecosystems. Furthermore, in preparation for 3GPP Release 19, 5GAA and ESA have jointly contributed key recommendations to advance mobility management for non-terrestrial networks. The 5GAA technical

21 https://www.harwellcampus.com/all-aboard-darwin-launches-trial-autonomous-passenger-shuttle-service-in-oxfordshire/
https://connectivity.esa.int/news/european-space-agencyfunded-continuously-connected-autonomous-shuttle-completes-twoyear-trial

report[22] calls for enhanced coordination between automakers, satellite operators, mobile network operators, and regulators to ensure an interoperable, secure, and scalable non-terrestrial network ecosystem. ESA's convening power and technical expertise make it uniquely positioned to orchestrate these multi-stakeholder collaborations. These include dynamic handover protocols, antenna performance thresholds, and terminal hardware specifications tailored to the automotive environment. Such collaboration ensures that vehicle connectivity requirements are represented in global standards from the outset. Some 3GPP contributions by the joint efforts of ESA and 5GAA can be summarised below:

Table 1: ESA and 5GAA Contributions to 3GPP Release Development

3GPP Release	ESA Contributions	5GAA Contributions
Release 17	Support for NTN waveforms and frequency bands	Input on C-V2X and initial NTN compatibility
Release 18	Use-case-driven testing through ARTES/ DARWIN	Service level definitions for mobility and vehicle density
Release 19	Joint recommendations with 5GAA for terminal design, antenna specs, and mobility handling	Standardisation roadmap for NTN-D2D, spectrum use, latency frameworks

Through initiatives such as the 'European Space-enabled Connectivity Solutions for the Car of the Future' workshop jointly organised by ESA, DLR and 5GAA, ESA continues to engage stakeholders in shaping the roadmap for connected mobility[23].

Additionally at Mobile World Congress (MWC) 2024 in Barcelona, during the first-ever 'Satellite and Non-Terrestrial Networks Summit,' ESA and the GSMA Foundry launched two major funding opportunities under the Space for 5G/6G programme line, one of which was the '5G Mobility Makerspace' initiative[24]. This initiative's focus is to accelerate the development of solutions, regulations, and industry standards for future vehicle connectivity. Participating companies were encouraged to focus on three key areas: the development of smart mobility antennas, the real-world validation of 5G interfaces, and the cross-sector applicability of NTN technology for broader transport applications, all of which are poised to greatly improve connectivity for the connected vehicles industry. ESA has further collaborated with OHB Systems to demonstrate vehicle-to-everything (V2X) services[25] and since 2022, ESA and the BMW Group[26] have a Memorandum of Understanding (MoU) with a view to share knowledge and ideas, create awareness, and promote opportunities for collaboration on hybrid and seamlessly integrated connectivity.

Looking ahead, ESA remains committed to expanding these partnerships and fostering further collaborations between the automotive, space, and digital industries. By leveraging expertise in satellite telecommunications, ESA continues to drive technological advancements that will enable a truly connected, autonomous, and globally competitive European automotive sector. With a commercially driven approach, ESA ensures that space-based connectivity solutions are seamlessly integrated with terrestrial networks, creating a sustainable, future-proof ecosystem for next-generation smart mobility.

22 https://5gaa.org/maximising-the-benefit-of-future-satellite-communications-for-automotive/
23 https://5gaa.org/events/european-space-enabled-connectivity-solutions-for-the-car-of-the-future/
24 https://connectivity.esa.int/news/european-space-agency-and-gsma-carry-forward-future-connectivity-after-mobile-world-congress-success
25 https://www.ohb.de/en/news/ohb-awarded-esa-contract-for-v2x-mission
26 https://connectivity.esa.int/news/tia-celebrates-automotive-memoranda-understanding-5gaa-and-bmw-group

4. THE COVERAGE GAP CHALLENGE

4.1 CONNECTIVITY AND THE ROLE OF HYBRID SOLUTIONS

The rapid advancement of connected car technology has introduced significant challenges in ensuring seamless and reliable connectivity across diverse geographical landscapes. A robust connectivity solution must integrate various communication technologies, optimising their mix while maintaining adaptability to future advancements. As outlined by 5GAA,[27] connected car applications will heavily depend on spectrum availability within mobile network infrastructures. However, current terrestrial network deployments face significant limitations in coverage as well as available spectrum, creating a pressing need for complementary solutions such as non-terrestrial networks.

Terrestrial Mobile Network Operators (MNOs) have historically prioritised building infrastructure in high-density urban areas and along major transportation routes due to economic considerations. As a result, large portions of rural, remote, and sparsely populated regions remain without adequate cellular coverage. In the UK, approximately 8% of geographical areas still lack even 4G services, and many users report poor network performance despite nominal coverage availability[2]. The situation is even more pronounced in larger countries such as Canada, where significant land areas remain disconnected due to the lack of economic incentives for MNOs to extend coverage.

Recent Efforts to improve rural coverage have included the use of lower frequency bands, such as the 600 MHz, 700 MHz, and 800 MHz bands, which offer enhanced penetration and reach. However, despite these deployments, complete terrestrial network coverage remains economically and geographically unfeasible.[11]

Furthermore, more efforts are needed to comprehensively assess global coverage on roads and in rural areas, although crowd-based assessments and Global System for Mobile Communications (GSM) coverage maps indicate significant disparities between countries and regions. The analysed gaps in coverage are further expanded on in the 5GAA's technical report[28]. This report has been produced during activities on non-terrestrial networks by 5GAA with strong ESA involvement and support, resulting in coordinated recommendations to 3GPP for Rel.19[23], as highlighted in a previous chapter. Novaspace also produced a map illustrating the percentage of connected Geographical Area[1] as illustrated in Figure 2. Similar results can be seen in a study of the Broadband Coverage in Europe 2023, created by the European Commission.

27 5GAA White Paper "Maximising the benefit of future satellite communications for automotive."
28 https://5gaa.org/maximising-the-benefit-of-future-satellite-communications-for-automotive/

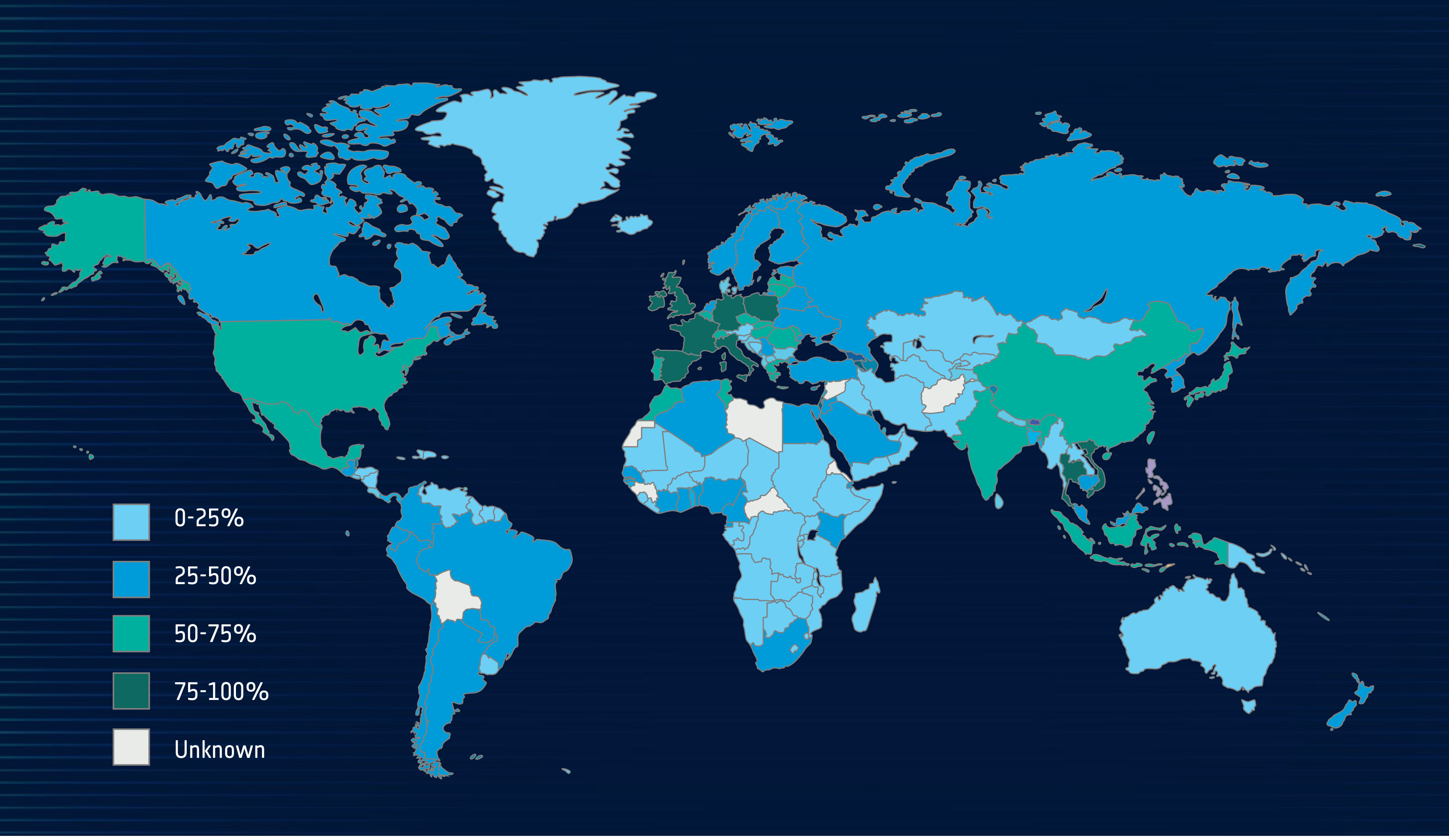


Figure 3: *% of Connected Geographical Area Worldwide.*
Source: Novaspace prospects for direct to handheld and IOT markets

To categorise terrestrial network coverage efficiency, the 5GAA has proposed a classification system based on coverage availability:

Table 2: Connectivity classification system based on coverage availability.

Densely Populated Small Countries	France and Germany have widespread terrestrial network coverage, ensuring reliable connectivity in most areas. Even so, coverage remains below 90% of fully connected local areas.
Sparsely Populated Small Countries	Some nations, particularly in Africa, have terrestrial network coverage concentrated in urban centres, capitals, and coastal areas, leaving rural regions underserved.
Large Countries Sparse Coverage in Remote Regions	Nations such as Australia, Canada, and the USA have well-covered urban and coastal areas but vast uncovered territories inland, creating substantial connectivity gaps.

Service-specific coverage loss can significantly impair performance, particularly for applications that depend on real-time data exchange. For example, if a vehicle passes through a coverage gap of 1.5 kilometres or more, services such as video streaming or real-time communications may experience noticeable interruptions. While brief gaps can be mitigated through buffering techniques, longer disruptions compromise the reliability of both critical and value-added services.

Different connected vehicle applications have varying levels of tolerance for network disruptions. Wideband services, such as infotainment and live voice or video communication, are sensitive to latency and require consistent high-bandwidth availability. These services rely on buffering to manage brief losses in signal but cannot withstand sustained outages. On the other hand, narrowband applications like vehicle telemetry and diagnostics are more resilient.

To address these challenges and maintain consistent service across varying geographies, automotive original equipment manufacturers (OEMs) are forming strategic partnerships with MNOs to implement advanced roaming capabilities. Traditionally, roaming SIM cards operate under standardised frameworks that support international roaming for general users and limited national roaming for emergency services. However, as the demand for uninterrupted in-vehicle connectivity grows, these models are being expanded to support broader and more dynamic roaming scenarios.

A key technological advancement supporting this shift is the adoption of embedded SIM (eSIM) and integrated SIM (iSIM) technologies. These solutions overcome the geographic and logistical limitations of traditional physical SIM cards, enabling remote provisioning and seamless switching between network providers. This flexibility allows OEMs to scale their connectivity solutions across markets and streamline operations without relying on manual SIM replacements or region-specific hardware.

Leading industry players are already applying these technologies in real-world deployments. Ericsson, for example, has demonstrated how eSIM adoption is enabling seamless global connectivity for the automotive sector, reducing cross-border integration complexity and enhancing user experience[29].

Similarly, BMW has implemented personal eSIM functionality in its vehicles throughout Europe, empowering users to link their mobile subscriptions directly to the car and maintain continuous service across national and international boundaries[30]. Complementing these efforts, companies such as Cubic Telecom provide full-service connectivity management platforms that support global IoT deployment. Their solutions enable OEMs to manage multiple MNO relationships, oversee network compliance, and deliver unified service experiences across diverse regulatory landscapes[31].

These developments reflect a broader trend toward removing national and technical limitations from automotive connectivity. As roaming frameworks evolve to support uninterrupted service beyond emergency-only scenarios, the inclusion of non-terrestrial networks represents the next logical step.

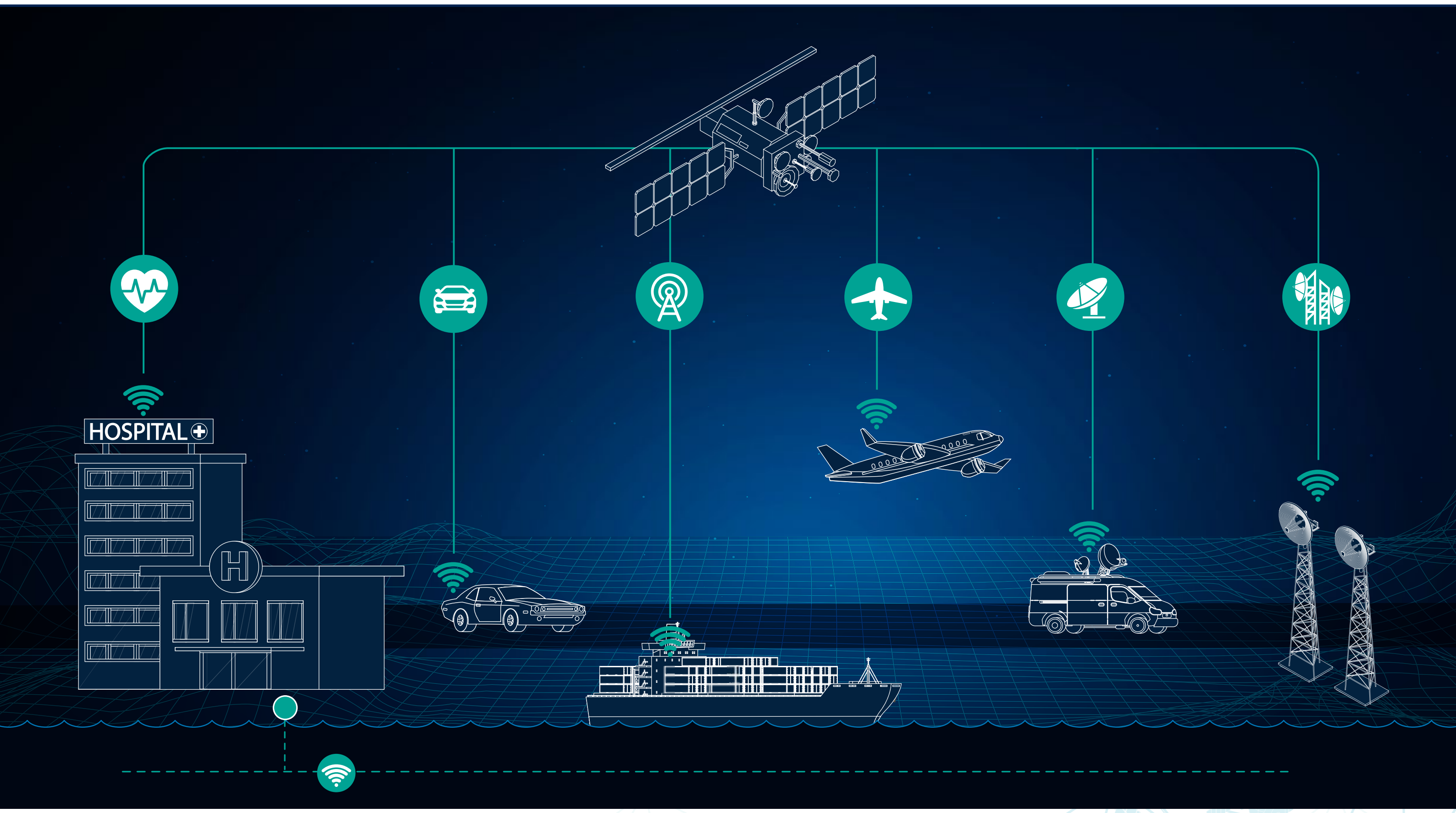
29 https://www.ericsson.com/en/blog/2020/9/esim-driving-global-connectivity-in-the-automotive-industry
30 https://www.iotinsider.com/transport/personal-esim-solution-for-bmws-available-across-europe
31 https://www.cubic3.com

The European Space Agency's Satis5 White Paper[32] highlights the advantages of satellite networks in supporting connected car ecosystems. Unlike terrestrial networks, satellite networks can provide connectivity across vast and remote areas without reliance on ground-based infrastructure, resulting in global coverage. Further, satellites can efficiently distribute data to multiple vehicles simultaneously via broadcast, reducing the strain on terrestrial networks. It is also a very timely solution for areas where terrestrial infrastructure is impractical or costly to establish. Finally, satellite communications offer robust security features and are less susceptible to localised network failures.

By leveraging these intrinsic benefits, a hybrid approach that integrates satellite and terrestrial networks can significantly enhance connectivity for connected vehicles. Many use cases, particularly those requiring persistent network access, can be better served through this model. Therefore, integrating satellite access into the roaming SIM ecosystem, vehicles can maintain consistent connectivity even in the most remote environments.

This hybrid connectivity model, leveraging both terrestrial and satellite networks, provides a comprehensive solution to the inherent limitations of either network type alone. Terrestrial networks offer high performance and capacity in dense population centres, while non-terrestrial networks ensure availability in rural, maritime, or mountainous regions. Extending existing roaming frameworks to encompass both network domains allows for seamless transitions and robust service continuity.

In summary, the rapid evolution of connected vehicle technologies demands a flexible and globally resilient connectivity architecture. Integrating terrestrial and non-terrestrial networks through a unified roaming approach, powered by technologies such as eSIM and iSIM, enables OEMs to deliver uninterrupted, high-quality service across all geographies. Achieving this vision will require close cooperation between OEMs, MNOs, satellite operators, and connectivity solution providers.



32 https://satis5.eurescom.eu/2020/11/27/satis5-publishes-white-paper/

4.2 VEHICLE DATA HANDLING

Connected vehicles, even today and at lower levels of autonomy, generate an immense volume of data, estimated at 4,000 gigabytes per day, while the average internet user will process 1.5 gigabytes – the ratio further illustrated on Figure 4. As self-driving capabilities advance, the complexity of the architecture supporting these systems will continue to grow, directly correlating with the number and sophistication of sensors required for autonomous operation. While the adoption of sensors has surged, this growth rate may not remain constant if there is no communications infrastructure to support this amount of data.

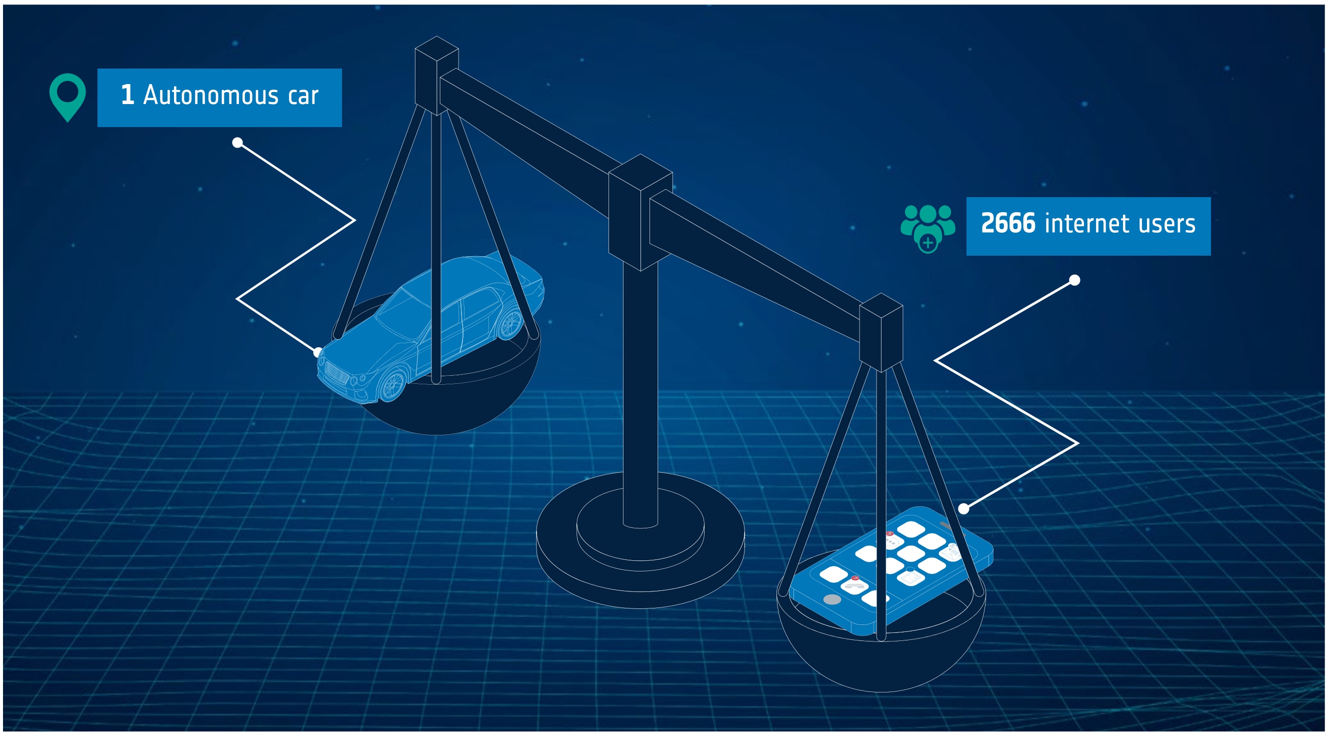


Figure 4: *Data comparison between 1 Autonomous vehicle and 2666 internet users*

Additionally, not all automotive sensors are the same. As they all serve distinct purposes and contribute differently to the overall data volume, it is essential that the communication system in place also allows for flexibility in required data rates and latency for sensible resource optimisation.

The specific configuration and combination of sensors within a vehicle significantly impact the total data output, with estimates from Stephan Heinrich – Previously a vehicle systems engineer at Lucid Motors[33] indicating that sensor-generated data bandwidth can reach up to 40 GBit/s (~19 TB/h). Even at the lowest estimate of 3 GBit/s (~1.4 TB/h), the volume of data is staggering. An example of some throughput requirements in accordance with the used sensor can be seen in the table below.

33 https://files.futurememorystorage.com/proceedings/2017/20170808_FT12_Heinrich.pdf

Table 3: Automotive sensors and their respective throughput requirements.

AUTOMOTIVE SENSORS		
Sensor	**Quantity**	**Generated data**
Radar	4-6	0.1-15 Mbit/s
LiDAR	1-5	20-100 Mbit/s
Camera	6-12	500-3500 Mbit/s
Ultrasonic	8-16	<0.01 Mbit/s
Vehicle motion, GNSS, IMU	-	<0.01 Mbit/s

To put this into perspective, a smartphone would be overwhelmed in less than 7 seconds with the amount of data coming from automotive sensors. On an annual scale, the numbers are even more striking. Based on current sensor data estimates, a single vehicle could generate between 380 TB to 5,100 TB of data annually[34].

However, not all this data will be stored on the car itself, nor would it be practical to transmit all raw sensor outputs given the extreme bandwidth requirements. In practice, only a subset of sensor data – such as vehicle motion, GNSS, IMU, and camera streams – are strong candidates for transmission via non-terrestrial networks (NTNs). For other sensors like radar, LiDAR, or ultrasonic, data is typically pre-processed into higher-level structures (e.g., detected objects) before being transmitted. This selective approach reduces the communication burden while still enabling cloud-based systems to play a vital role, making ubiquitous connectivity essential for efficient downstream and upstream flows of relevant information.

To fully grasp the implications of this tremendous amount of data, it is essential to understand that not all autonomous vehicles operate under the same technical requirements. The Society of Automotive Engineers (SAE) International, a globally recognised authority in automotive standards, has developed a six-tier classification system that defines the different levels of vehicle automation.[35] These levels range from 0, which includes no automation and relies entirely on human control, to 5, which represents full automation with no human intervention required. An overview of this classification can be found in the table below.

Table 4: Levels of Automation in Autonomous Cars according to SAE

AUTOMATION LEVELS OF AUTONOMOUS CARS		
LEVEL 0	No Automation	No automated features.
LEVEL 1	Driver Assistance	One task at a time system.
LEVEL 2	Partial Automation	Two or more automated features.
LEVEL 3	Conditional Automation	Can perform all aspects of dynamic driving but still needs driver-on-request.
LEVEL 4	High Automation	The car can be driverless in certain conditions.
LEVEL 5	Full Automation	Can perform all aspects of driving in any environment.

34 https://www.tuxera.com/blog/autonomous-cars-300-tb-of-data-per-year/
35 https://www.sae.org/blog/sae-j3016-update

The industry's push toward greater automation is further accelerating the need for sophisticated data management solutions. As of today, the most advanced commercial vehicles on the market operate at Level 2 autonomy, where driver assistance features like lane-keeping and adaptive cruise control require continuous human supervision. Some automakers have already developed Level 3 autonomous vehicles, capable of handling certain driving tasks without human intervention, but these remain subject to regulatory approval. Although Level 4 autonomy has taken longer to reach commercialisation than initially anticipated, several manufacturers have advanced to the field-testing phase. Companies such as Tesla are actively working to bridge the gap between Level 4 and fully autonomous Level 5 vehicles.[36]

As vehicles progress toward higher levels of automation, the volume of data they generate will continue to expand. Each step forward requires more sophisticated sensor networks, real-time computing capabilities, and artificial intelligence-driven analytics. The transition from Level 2 to Level 4 autonomy alone demands a significant increase in perception capabilities, with advanced light detection and ranging (LiDAR), radar, ultrasonic, and high-resolution camera systems feeding vast amounts of data into onboard processors. This data must be processed with near-instantaneous response times to ensure safety and efficiency in complex driving environments.

As storage constraints make it impractical to retain all sensor data within the vehicle, automakers are increasingly turning to cloud computing and edge processing solutions, enabled by continuous connectivity. By leveraging New Radio Vehicle-to-Everything (NR-V2X) communication, cars will be able to offload non-critical data to cloud infrastructure while processing essential real-time data locally. This hybrid approach ensures that critical driving decisions remain instantaneous while long-term storage and analytics occur offboard.

This exponential increase in vehicle data generation marks a critical juncture in the evolution of automotive systems. Modern vehicles are no longer isolated mechanical units but are instead becoming data-centric platforms, continuously interacting with external ecosystems through software, sensors, and real-time analytics. This transformation demands not only robust internal processing capabilities but also permanent connectivity to manage, transmit, and act on this data.

This shift is explored in a recent study commissioned by European Space Agency's Commercialisation Gateway and led by Einstein Ventures[37], a European investment firm focused on space-enabled downstream applications. To strengthen the research, Einstein subcontracted Porsche Consulting[38] and Acitoflux[39], both of which bring deep experience in space technologies and the automotive sector. The study team also included experts from SAP[40] and OHB SE, a leader in satellite manufacturing. More than 30 senior executives from across the automotive and mobility ecosystem contributed insights through interviews, lending further depth to the findings[41].

36 https://www.tesla.com/en_gb/support/autopilot
37 https://www.einstein-iv.space/
38 https://www.porsche-consulting.com/international/en/homepage
39 https://www.acitoflux.com/
40 https://www.sap.com/uk/index.html?geotargering_redirect=true
41 https://www.einstein-iv.space/space-enabled-applications-in-the-automotive-sector

The research highlights the emergence of software-defined vehicles (SDVs) as a disruptive force. Unlike traditional vehicles, whose development cycles are dominated by hardware upgrades, SDVs rely on software updates and digital service layers, often delivered over-the-air (OTA). These new models foster shorter innovation cycles and introduce subscription-based revenue streams. However, as further explored, this transformation introduces an urgent dependency on seamless and secure connectivity.

The study argues that such a shift can only reach its full potential in the "SatCom era," a period characterised by constant, global connectivity enabled by satellite communication infrastructure.

In this context, the current infrastructure is deemed insufficient to support the sheer volume and velocity of data exchanges required by SDVs and keep up with the ever-increasing innovative vehicle features.

Therefore, the move toward software-defined architectures will not only redefine vehicle design and production but will also necessitate a complete rethinking of data infrastructure. The ability to manage and monetise vehicle data effectively will hinge on the industry's capacity to integrate satellite communication as a foundational enabler of the connected vehicle future.

5.0 ENABLING TECHNOLOGIES

5.1 NOTABLE DRIVERS

As the automotive sector advances toward an era defined by full connectivity, the role of some enabling technologies becomes increasingly pivotal. While much of the public and industry attention remains fixed on primary infrastructure, secondary drivers such as antenna systems, Low Noise Amplifiers (LNAs), and IP cores are proving just as vital to ensuring seamless interoperability between terrestrial and space-based assets. These components, while less visible, form the bedrock of the high-speed, resilient, and scalable connectivity required to support next-generation connected and autonomous vehicles.

Antenna technology, and most notably flat-panel antennas adapted to mobility, have become the key enablers of satellite-to-vehicle communication. In addition to their convenient form factor, they are also electronically steerable, which translates to rapid adjustments of their beam direction without mechanical movement — essential in dynamic vehicular environments. With the backing of the European Space Agency, significant research has gone into developing compact, low-profile antennas suitable for vehicle integration.

Among the most notable developments is the work of Kymeta[42] who have engineered flat-panel automotive antennas based on metamaterials. These are being tested on vehicle platforms for constant connectivity while in motion[43].

In Europe, SatixFy[44] is involved in the development of advanced digital beamforming antennas that can be embedded into vehicles and dynamically track LEO satellites. Hensoldt Nexeya[45], primarily known for defence applications, is adapting their ruggedised antenna systems to support commercial vehicular connectivity, especially in heavy-duty remote-use scenarios. These antenna systems typically support multi-band operation across Ku, Ka, and L bands, ensuring compatibility with a range of satellite networks and optimising performance under various environmental conditions.

Equally indispensable are LNAs, which amplify weak satellite signals received by the antenna while adding minimal noise. In mobile environments, especially those with inconsistent signal strength such as tunnels, rural highways, or mountainous regions, LNA performance determines the reliability and clarity of the vehicle's data link. Infineon Technologies[46] is a leader in this field, well positioned for producing automotive-grade LNAs. Their amplifiers are based on advanced gallium nitride (GaN) and silicon-germanium (SiGe) technologies, enabling excellent noise figures and high linearity under harsh thermal conditions.

42 https://www.intelsat.com/wp-content/uploads/2020/08/8482-FlexMove-Kymeta-u8-Product-Sheet.pdf
43 https://www.kymetacorp.com/about/news-insights/innovation-in-motion-kymetas-power-efficient-solution-for-on-the-move-multi-orbit-satellite-communications
44 https://www.satixfy.com/
45 https://www.hensoldt.net/company/country-hubs/france
46 https://www.infineon.com/

Qorvo[47] offers a range of LNAs optimized for both satellite and terrestrial 5G communication, used in systems where thermal management and signal integrity are mission critical.

Many of these developments are supported through EU-funded research programs such as Horizon Europe and ESA's ARTES, which encourage the transfer of space-proven hardware into commercial automotive platforms.

Seamless network handover is another vital requirement for connected vehicles. As a vehicle moves between urban areas with strong terrestrial 5G coverage and remote locations where only satellite service is available, it must switch between networks without interrupting connectivity. This process relies heavily on IP cores, which are reusable logic blocks embedded into communication chipsets that handle protocol management and handover logic. Imagination Technologies[48] has developed IP cores that support real-time multi-network handover with secure data encryption, designed specifically for V2X environments. Arm[49], through their Neoverse platform, is delivering IP cores that support the scalable edge computing needed to manage multiple connectivity streams with low latency, ideal for use in autonomous driving systems. Intel[50], via their acquisition of Altera, provides programmable IP solutions for software-defined radios and network switching chips that manage dynamic handover between 5G, Wi-Fi, and satellite domains.

These technologies enable vehicles to maintain continuous data transfer, whether communicating vehicle telemetry to the cloud, updating over-the-air software, or interacting with smart infrastructure.

The development and harmonisation of these handover technologies are not occurring in isolation. They are being shaped by several industry-wide standardisation efforts. The European Telecommunication Standards Institute (ETSI) Technical Committee on Intelligent Transport Systems (ETSI TC ITS)[51] is actively defining communication protocols to support hybrid handover scenarios and interoperability between terrestrial and satellite V2X networks.

Artificial intelligence is an increasingly popular enabling technology for smart and autonomous vehicles. In a very recent announcement, Magna, a global leader in mobility technology, is collaborating with NVIDIA to utilise their NVIDIA DRIVE AGX - system-on-a-chip (SoC) solution[52]. The project is set to achieve cutting-edge AI functionalities adding value to varying levels of autonomous driving (AD) and interior cabin applications.

47 https://www.qorvo.com/
48 https://www.imaginationtech.com/
49 https://www.arm.com/products/silicon-ip-cpu/neoverse/neoverse-n1
50 https://www.intel.com/content/www/us/en/homepage.html
51 https://www.etsi.org/committee/1402-its
52 https://www.nvidia.com/en-gb/self-driving-cars/in-vehicle-computing/

Meanwhile, 3GPP continues to evolve the specification of its standards under Release 18 and beyond, including advanced support for non-terrestrial networks and the integration of satellite access within the broader 5G ecosystem[53]. These efforts are crucial in ensuring that connected vehicles can function consistently regardless of geography or infrastructure availability.

On the collaborative front, numerous European and global initiatives are pushing the envelope of automotive-satellite integration. For example, 5GAA[54] brings together carmakers such as BMW and Volkswagen, telecom providers, and satellite operators like Viasat to explore hybrid communication strategies, including the use of space-based assets to augment terrestrial coverage.

The European Space Agency's Space for 5G & 6G initiative aims to bridge the aerospace and mobility sectors, supporting projects that develop multi-network communication terminals and shared spectrum access strategies[55]. Here, under a digital transformation project titled 5G-EMERGE[56], a use case category titled Direct-to-vehicle is being studied, accessed and developed on a technology level in collaboration with many subcontractors such as MinWave[57], Keysight[58] and many others.

Simultaneously, the CAR 2 CAR Communication Consortium[59], based in Europe, works to harmonise vehicle communication protocols across borders, with a specific interest in standardising V2X use cases that rely on both terrestrial and space infrastructure.

Together, these technologies form an indispensable layer in the broader digital architecture of the connected vehicle. Antennas, LNAs, IP cores, and handover protocols may not be visible to drivers or fleet operators, but they underpin every real-time application — from navigation and infotainment to autonomous driving and over-the-air diagnostics. As such, they are no longer secondary, they are foundational.

53 https://www.3gpp.org/technologies/ntn-overview
54 https://5gaa.org/
55 https://connectivity.esa.int/space-5g-6g
56 https://connectivity.esa.int/projects/5gemerge
57 https://www.minwave.ch/
58 https://rentaltec.com/manufacturers/keysight/?gad_source=1&gad_campaignid=19637260008&gbraid=0AAAApSxhrMCkhXQw-kekFB2J0eDFE-pB&gclid=Cj0KCQjwlMfABhCWARIsADGXdy8oSJfxV0ik9fH1yaXuPlsny5U6IOmV0ESZ-FhDuRTqahEmTjHFJJQaAl_QEALw_wcB
59 https://www.car-2-car.org/

5.2 SATELLITE CONSTELLATIONS

Low earth orbit (LEO) satellites orbit the Earth at altitudes between 500 and 1,500 km, significantly reducing signal transmission delays to as low as 20-50 milliseconds[1]. As such, they are providing low- latency, high-bandwidth, and globally available connectivity. They've proven essential for the advancement of smart and autonomous vehicles. This capability allows autonomous vehicles to access and process large volumes of data, including detailed maps, real-time traffic conditions, weather updates, and essential software upgrades, all of which are fundamental to self-driving vehicle performance.

Geostationary orbit (GEO) satellites operate at altitudes of approximately 35,786 km and provide wider coverage of the Earth and Doppler shift independence, making them ideal for broadcasting services, software updates, and emergency communications to vehicles. Although their higher latency (typically around 500 milliseconds round-trip) limits their use for real-time control in autonomous driving, they excel at providing robust backup connectivity, essential for infrequent data transmissions in mobility scenarios.

Additionally, Medium Earth Orbit (MEO) satellites, positioned at altitudes between 2,000 and 35,786 km, provide a middle-ground solution, balancing coverage area with moderate latency suitable for certain automotive applications where ultra-low latency is less critical.

Unlike terrestrial cellular infrastructure, which may be unreliable or unavailable in remote or rural areas, satellites can provide seamless, ubiquitous coverage, ensuring autonomous vehicles remain connected regardless of location. Importantly, the convergence between Terrestrial Networks (TN) and Non-Terrestrial Networks (NTN), ensures complementary and robust connectivity solutions, as satellite constellations alone could not handle the traffic of millions of vehicles. Satellites effectively augment terrestrial systems, enhancing connectivity reliability and resilience across diverse geographical and operational conditions. Vehicles can also benefit from a multi-orbit, multi-layered communication topology that integrates low-latency inter-satellite links (ISLs) with high-speed ground station gateways to provide service or complement existing Cellular Vehicle-to-Everything (C-V2X) technologies while utilising spacecraft of various orbits and therefore providing diverse benefits. ISL architectures are particularly beneficial for connected and autonomous vehicles operating in remote areas.

Additionally, the advanced beamforming techniques allow LEO satellites to dynamically allocate bandwidth and coverage based on real-time vehicular density, ensuring optimal load balancing across regions with fluctuating network demand. This is crucial for automotive applications such as real-time HD mapping, predictive maintenance, and vehicle telematics. Autonomous vehicles require Ultra-Reliable Low-Latency Communications (URLLC) to make split-second driving decisions based on data from sensors, cameras, and cloud-based AI algorithms. To answer that demand, some constellations are incorporating edge computing

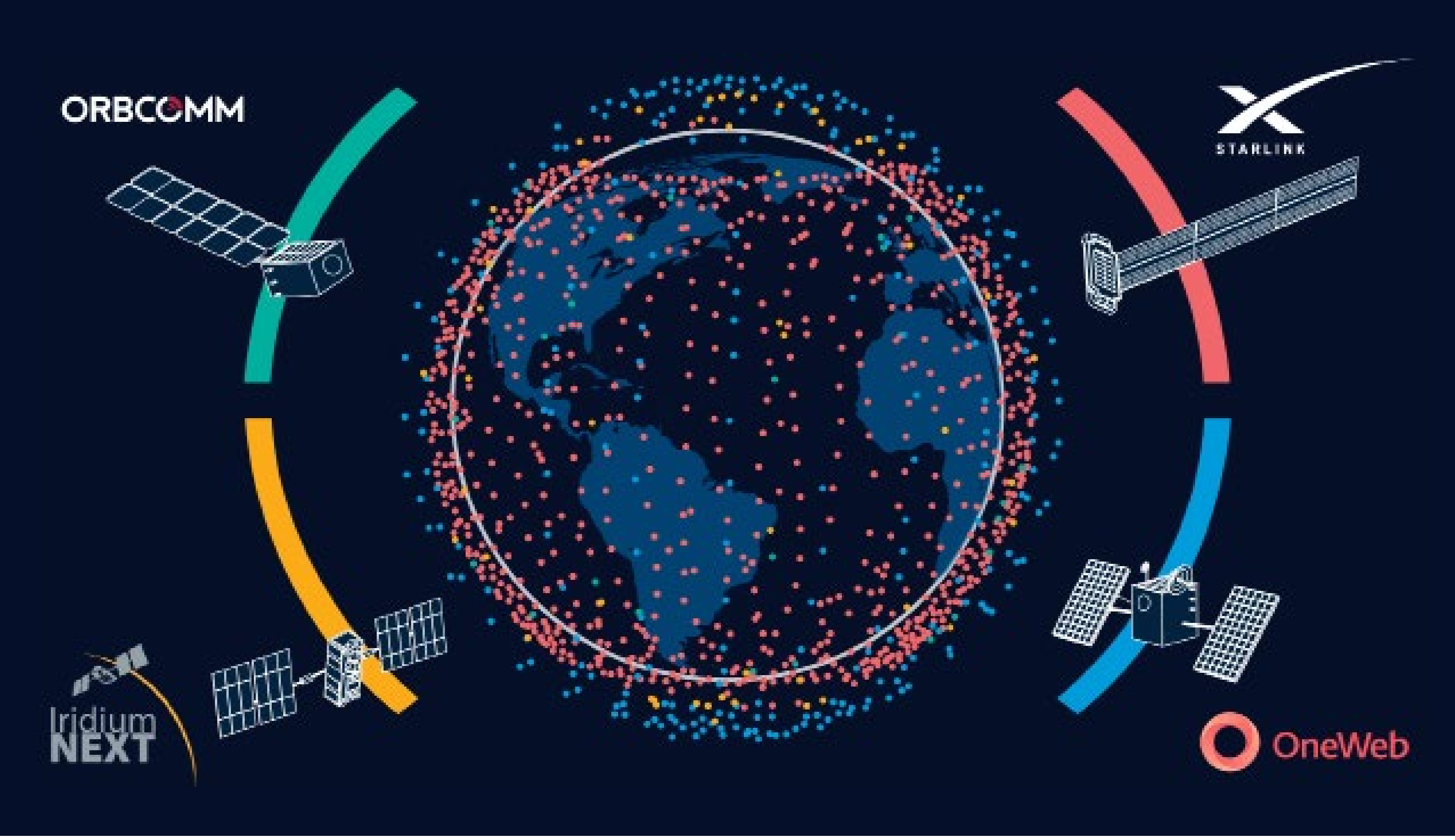


Figure 5: *LEO satellite constellation major industry leaders.*

capabilities onboard the satellites, enabling localised processing of automotive telemetry data before downlinking to terrestrial cloud servers. This reduces also end-to-end latency, allowing connected and autonomous vehicles to make faster driving decisions without relying solely on distant cloud processing centres.

Finally, satellite constellations provide the necessary infrastructure to ensure global roaming capabilities, allowing vehicles to remain connected across international borders without reliance on local telecommunication networks. This is particularly relevant for commercial fleets and logistics companies that require consistent, high-speed connectivity for route optimisation, fleet management, and remote diagnostics.

While some startup are attempting a focused, logistics-oriented strategy (such as Unio Enterprise)[60], the competitive landscape includes established satellite operators such as SES[61] and Eutelsat[62], which are pursuing similar hybrid network solutions. Additionally, Starlink, with their rapidly expanding LEO constellation, has already demonstrated disruptive potential in this domain, reshaping expectations around bandwidth, latency, and market access.

60 https://www.unio.global/
61 https://www.ses.com/
62 https://www.eutelsat.com/en/home.html

5.3 DIRECT TO DEVICE

Direct-to-device satellite connectivity is a much-needed cornerstone of global automotive communications infrastructure, providing high-availability data links for vehicles regardless of their geographic location. Among all industries impacted by direct-to-device technologies, the automotive sector stands out as one of the most commercially promising and technically reliant. According to GSMA Intelligence, the connected vehicle market is expected to exceed $215 billion by 2027, as informed by the exponential technological growth of in-vehicle features[63].

Historically, satellite communications have played a crucial, though limited, role in crisis connectivity, particularly where cellular infrastructure is destroyed or absent. However, these systems have traditionally relied on bespoke terminals, effective only within small operational zones and typically lacking mobility support. With climate-driven disasters growing in intensity and frequency, a resilient and flexible network solution becomes critical infrastructure. Over 900 mobile sites were knocked out during Ireland's record-breaking storm in early 2024 alone, leaving over one million people without coverage[64]. Similar vulnerabilities exist across Europe.

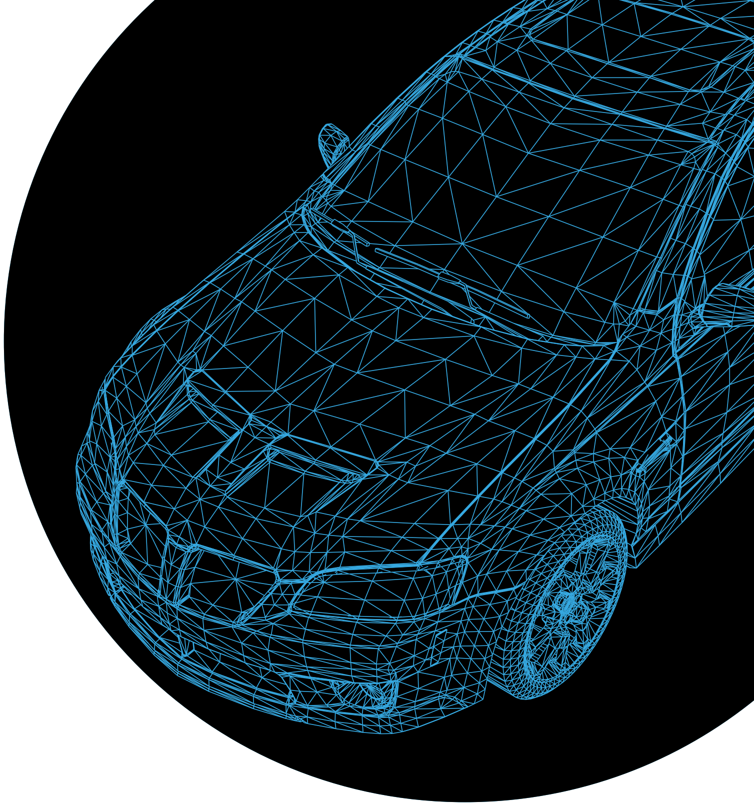
Direct-to-device changes this. Unlike traditional satellite communications that require bulky ground terminals, direct-to-device connectivity allows vehicles to receive satellite signal using compact, integrated flat antennas. This ensures uninterrupted communication in remote regions, as well as connectivity during environmental disasters where terrestrial cellular networks and ground terminals may be affected.

At the core of direct-to-device implementation, capable of keeping up with the ever-evolving automotive landscape, is the evolution of 5G non-terrestrial networks within the 3GPP standards framework. Release 17 formalised foundational capabilities, including non-terrestrial network architecture, waveform specifications, and support for enhanced narrowband internet of things (NB-IoT) via satellite. Release 18 introduces advanced features such as AI-driven spectrum allocation, inter-satellite routing, satellite-assisted mobility management, and support for ultra reliable low latency communications — a core requirement for connected vehicles[65].

At the same time, it is important to ensure network redundancy via the utilisation of existing terrestrial infrastructure. This is achieved through advanced beam-switching algorithms and frequency agility, allowing vehicles to dynamically connect to the nearest satellite and/or terrestrial cell tower.

One of the technological breakthroughs enabling the direct-to-device advance is dynamic beamforming and beam tracking. As satellites move quickly across the sky, the antenna system onboard the vehicle must maintain constant alignment to the satellite's beam using data and prediction algorithms. Doppler shift compensation is critical, as the high relative velocity between the satellite and the vehicle can cause frequency distortions that degrade signal quality. Sophisticated signal processing algorithms embedded in the radio modules correct these shifts dynamically, ensuring stable communications even when the vehicle is moving at highway speeds.

63 https://www.gsmaintelligence.com
64 https://www.independent.ie/irish-news/over-one-million-users-still-without-mobile-coverage-or-broadband-after-storm-eowyn/a2056651609.html
65 https://www.3gpp.org/news-events/partner-news/ntn-rel17



Power efficiency is another engineering hurdle being addressed through the development of hybrid and digital beamforming architectures. These allow direct-to-device-capable modules to consume power comparable to traditional 4G/5G modems, making them feasible for installation across consumer vehicles without impacting vehicle battery performance.

Finally, latency is also a determining factor in system architecture: LEO satellite systems typically provide end-to-end latency of around 35 ms, MEO systems approximately 95 ms, and GEO systems can exceed 285 ms. These parameters directly influence the viability of direct-to-device use cases.

Several companies have launched ambitious initiatives that bring these capabilities to market. SpaceX, in partnership with T-Mobile, has rolled out the Starlink direct-to-cell project, with over 349 D2D-capable satellites deployed as of December 2024 and expectations to surpass 1,000 by the end of 2025[66]. AST SpaceMobile has completed the first space-enabled voice call using an unmodified smartphone through their BlueBird satellite and has attracted significant investment from AT&T, Vodafone, and Google[67]. Lynk Global has focused on commercial expansion in over 50 countries, signing agreements with more than 40 mobile network operators to offer emergency messaging and basic voice services[68]. Apple and Globalstar introduced emergency SOS via satellite for iPhones starting with the iPhone 14, marking one of the first large-scale consumer deployments of direct-to-device capabilities in smartphones[69]. Additionally, Digital Decade 2030 policy[70] identifies satellite communications as essential to Europe's competitiveness in transport, energy, and defence.

Viasat[71], following its acquisition of Inmarsat, has successfully trialled automotive-grade direct-to-device connectivity in Brazil, in partnership with GuardianSat[72] and Skylo[73]. These trials demonstrated vehicles maintaining connectivity over Inmarsat's L-band network using 3GPP-compliant modules from Quectel[74]. By integrating satellite and cellular fallback in real time, vehicles could send location, status, and emergency data without disruption across varying network conditions. These narrowband trials validate the readiness of the technology for automotive-grade use cases and support further scaling towards broadband applications.

The UK is taking a proactive regulatory stance through Ofcom[75], who launched a consultation in March 2025 to explore enabling satellite direct-to-device services in mobile spectrum bands below 3 GHz[76]. Proposed licensing models include licence exemptions, MNO spectrum variations, and

66 https://www.starlink.com/business/direct-to-cell
67 https://uk.pcmag.com/networking/156488/ast-spacemobiles-new-satellites-successfully-power-video-call
68 https://spacenews.com/mda-space-to-build-satellites-for-globalstars-apple-backed-next-gen-constellation/
69 https://spacenews.com/mda-space-to-build-satellites-for-globalstars-apple-backed-next-gen-constellation/
70 https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/europe-fit-digital-age/europes-digital-decade-digital-targets-2030_en
71 https://www.viasat.com/
72 https://gsat.space/
73 https://www.skylo.tech/
74 https://www.quectel.com/
75 https://www.ofcom.org.uk/
76 https://www.ofcom.org.uk/spectrum/space-and-satellites/consultation-enabling-satellite-direct-to-device-services-in-mobile-spectrum-bands

new terminal licences. Ofcom's broader initiatives include transitioning satellite terminal licensing to a light-touch regime and coordinating with European stakeholders on harmonised spectrum use for satellite IoT and mobile services. These developments position the UK as a potential regulatory provider for global deployment, especially with key spectrum decisions pending at the World Radiocommunication Conference in 2027[77].

Europe's regulatory and strategic readiness, however, remains under scrutiny. Italian Prime Minister Giorgia Meloni recently lamented the lack of a viable European alternative to US-led direct-to-device systems[78]. Within the current landscape, no single vertical market is large enough to close the business case on its own. However, European actors are actively reshaping the market towards direct-to-device services.

The European Space Agency's response to these dynamics has been the launch of a direct-to-device initiative to support industry in testing, validating, and scaling end-to-end direct-to-device systems. During its latest stakeholder workshop, ESA identified the need for collaborative investment models, public co-funding, and standardised hardware components to reduce development costs[79]. The use of space spectrum such as the 2 GHz mobile satellite service (MSS) S-band is under review for future licensing frameworks, while technical challenges such as RF agility, industrial antenna production, and the integration of space-compatible 5G base stations (onboard gNodeBs) remain focus areas for innovation.

As a product of ESA's alignment with 5GAA's technical assessments, key considerations for satellite-based direct-to-device connectivity include antenna design feasibility and frequency band trade-offs. Notably, L-band and S-band frequencies offer advantages in terms of penetration and resilience, while Ka-band supports higher data throughput but requires more sophisticated user equipment. These trade-offs are crucial in balancing cost, complexity, and performance in vehicular terminals.

Direct-to-device satellite connectivity is set to revolutionise how vehicles stay connected — enabling coverage in remote regions, improving road safety and disaster preparedness through uninterrupted emergency services, and supporting new models of predictive maintenance and autonomous navigation. As terrestrial networks struggle to fulfil all connectivity needs, direct-to-device communications serve as a resilient overlay that guarantees continuity of service. With billions in projected economic impact and a transformative effect on both consumer experience and industry operations, direct-to-device connectivity is becoming an indispensable pillar of future automotive ecosystem.

77 https://www.gsma.com/connectivity-for-good/spectrum/the-road-to-wrc-27-a-new-cycle-begins/
78 https://www.politico.eu/sponsored-content/why-europes-satellite-policies-must-support-a-new-era-of-connectivity/
79 https://connectivity.esa.int/directtodevice-connectivity-opportunity-europe

5.4 VEHICLE-TO-EVERYTHING (C-V2X)

Vehicle-to-Everything (V2X) communication is a core enabling technology in the evolution of intelligent transportation systems, facilitating direct and network-based data exchange between vehicles, infrastructure, pedestrians, and other road users. Among the competing technologies, Cellular Vehicle-to-Everything (C-V2X) has emerged as a superior choice due to its performance, scalability, cost-efficiency, and alignment with future mobile networks.

Initially introduced in 3GPP Release 14 in 2017, C-V2X was designed to operate on existing long-term evolution (LTE) infrastructure[80]. It supported two communication modes: direct communication via the PC5 interface for short-range, low-latency interaction between vehicles and nearby objects, and network-based communication via the Uu interface between vehicles and cellular base stations. This dual-mode approach provided immediate advantages over older technologies like DSRC, which requires a separate greenfield deployment of roadside units and dedicated spectrum[81]. Real-world trials and academic studies have consistently shown that C-V2X outperforms DSRC in several key metrics, including spectral efficiency, communication range, transmit power usage, and reliability. Unlike DSRC, C-V2X leverages the globally widespread LTE infrastructure, allowing for faster deployment and reduced operational costs. DSRC's lack of integration with the mobile telecommunications roadmap places it at a disadvantage, especially as the world moves toward 5G and beyond[82].

The C-V2X standard was shaped through extensive collaboration among technology providers, automakers, and regulatory agencies. Qualcomm[83] was one of the earliest and most significant contributors, submitting the foundational LTE-V2X proposal to 3GPP. Their technology formed the basis for the PC5 interface. This standardisation effort was supported by major telecommunication companies such as Huawei, Ericsson, and Nokia, along with automotive leaders including Ford, Audi, BMW, and Volkswagen. Organizations like the 5G Automotive Association (5GAA) coordinated field trials and lobbied for regulatory acceptance.

While the introduction of this technology assumed operations within the limits of LTE or otherwise referred to as 4G, insufficient for the stringent requirements of autonomous driving[84], the C-V2X framework was later significantly enhanced with the emerge of 5G in 3GPP Release 16. Those added capabilities like dynamic sidelink communication and URLLC, allowed vehicles to share real-time sensor data, high-definition maps, and manoeuvre intentions with unprecedented speed and reliability. One of the most transformative developments in later 3GPP releases is the introduction of NTN to the 3GPP standardisation framework. This evolution, developed through Releases 17, 18, and continuing in 19, addresses one of the fundamental limitations of terrestrial cellular networks such as lack of coverage in rural, remote, or disaster-affected areas. It allowed for continuous, global vehicle connectivity, essential for long-haul freight transport, rural mobility, and resilient emergency communication systems.

80 https://portal.3gpp.org/desktopmodules/Specifications/SpecificationDetails.aspx?specificationId=3179
81 https://5gaa.org/content/uploads/2018/08/V2X_white_paper_v1_0.pdf
82 Moradi-Pari, Ehsan & Tian, Danyang & Bahramgiri, Mojtaba & Rajab, Samer & Bai, Sue. (2023). DSRC Versus LTE-V2X: Empirical Performance Analysis of Direct Vehicular Communication Technologies. IEEE Transactions on Intelligent Transportation Systems.
83 https://www.qualcomm.com/
84 https://www.5gamericas/- Vehicular Connectivity- C-V2X and 5G.

Organizations like the European Space Agency and 5GAA amongst others have been instrumental in piloting the standardisation of non-terrestrial network V2X connectivity.

The addition of Frequency Range 2 (FR2) and millimetre-wave (mmWave) spectrum in later C-V2X implementations boosts data throughput dramatically. This is critical for advanced use cases like collective perception, where vehicles, infrastructure, and cloud services share raw sensor feeds, such as light radar (LiDAR) or camera data, to build a comprehensive, real-time model of road conditions. Such capabilities are particularly valuable in dense urban areas where line-of-sight communication is often obstructed.

C-V2X is also tightly integrated with emerging computing paradigms, such as mobile edge computing (MEC) and AI-assisted communication. By offloading intensive computational tasks to edge servers, vehicles can reduce latency and improve decision-making in real time. AI-based communication protocols under development in Release 19 will further optimise network performance by prioritising safety messages and learning from past communication patterns to allocate resources more efficiently[85]. These enhancements are particularly important for battery-operated V2X devices, where energy efficiency is a critical concern.

The commercial rollout of C-V2X has been evolving in parallel, with companies like Fibocom offering commercially available automotive-grade modules[86]. In China, the rollout of C-V2X is happening at citywide scale backed by government and industry. One major deployment is in Wuxi, Jiangsu – China's first national C-V2X pilot city – where since 2017 a citywide C-V2X network has been installed by China Mobile and Huawei in cooperation with the Ministry of Public Security's research institute[87]. This project covers roughly about 280 km of roads with hundreds of smart roadside units and connected traffic signals, enabling vehicles to communicate in real time with intersections and other cars. By 2019 the Wuxi pilot expanded to 400 equipped intersections and was processing over 1.6 petabytes of traffic data per day, yielding applications like collision warnings and emergency brake alerts for drivers[88]. More broadly, China has made C-V2X a pillar of its national transportation strategy: automakers began mass-producing C-V2X-equipped models in 2020, and by 2024 over 500,000 vehicles in China have been outfitted with V2X systems[89].

In the United States, significant C-V2X deployments have taken the form of pilot programs led by automakers and state agencies. For example, Audi launched a year-long deployment in Virginia in partnership with the Virginia Department of Transportation (VDOT), Qualcomm, American Tower and others to equip select Audi vehicles with C-V2X for safety messaging[90].

In Germany, C-V2X technology has been implemented in both industry-led trials and government-funded infrastructure pilots. In one trial, Vodafone Germany, together with Huawei and auto supplier Bosch, integrated C-V2X connectivity with a car's adaptive cruise control system to enable "connected" cruise control – test vehicles could automatically adjust speed based on real-time traffic data received from other cars and roadside units, effectively allowing them to autopilot in rush hour by seeing beyond the driver's line of sight[91]. Separately, the German Federal Ministry of Transport (BMVI) launched the KoMoD testbed in Düsseldorf, a €15 million project that equipped a 20 km stretch of highway and

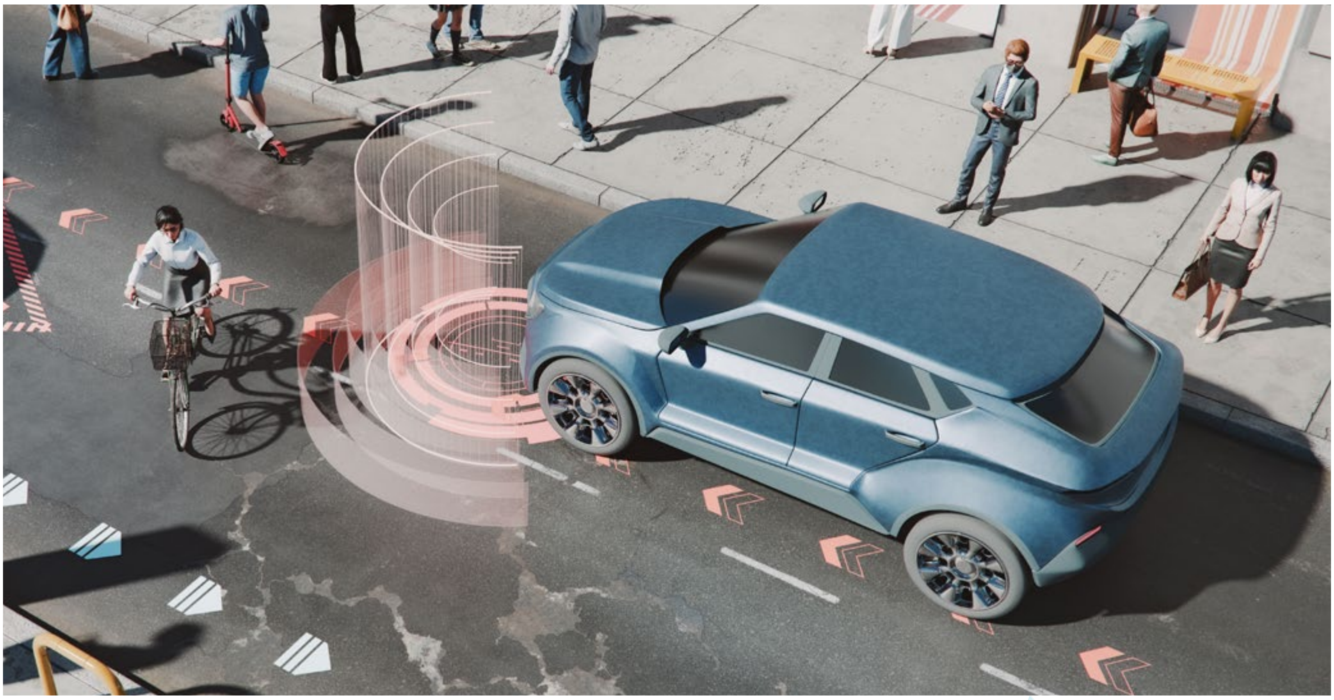
85 Introduction to 3GPP Release 19 and 6G Planning
86 https://www.fibocom.com/en/5gFeaturePage2176/info_itemid_1989.html
87 https://www.chinadaily.com.cn/m/jiangsu/wuxi/2019-05/17/content_37471118.htm#:~:text=The%20world%27s%20first%20city,driving%20will%20also%20be%20built
88 https://technode.com/2019/06/28/china-wuxi-v2x-2019/#:~:text=With%20more%20than%202%20million,general%20manager%20at%20China%20Mobile
89 Global and China Passenger Car T-Box Market Report 2025: Demand and Impact of Automotive V2X, 5G, Satellite Communications and Other Functions - ResearchAndMarkets.com
90 Audi's V2X Research is Paying Off for Work Zone Traffic Safety
91 https://www.mobileeurope.co.uk/vodafone-teams-up-with-huawei-bosch-in-germany-c-v2x-trial/#:~:text=match%20at%20L117%20The%20trial,vehicle%20in%20front%20using%20radar

urban roads with intelligent traffic infrastructure for V2X communication[92]. This Düsseldorf pilot — which involved city authorities and companies like Vodafone and Siemens — demonstrated use cases such as green light optimal speed advisory and work-zone hazard alerts under everyday driving conditions.

Across Europe, C-V2X deployment is advancing through cross-border collaborations and city pilots supported by the European Union and industry consortiums. A prime example is the EU-funded 5G-CroCo project, which established a connected corridor for C-V2X along highways spanning France, Germany, and Luxembourg. In 2020–2021, trial vehicles from various European manufacturers drove this route and were able to seamlessly exchange data across national borders, testing scenarios like cooperative driving and automated lane changes while handing off between different countries' mobile networks[93]. This cross-border pilot, involving various European telecom operators and automakers, demonstrated that C-V2X can maintain low-latency, reliable communication for safety and autonomous driving even as vehicles transition between network zones, an important step toward pan-European connected mobility.

Another implementation of C-V2X was done by the C-Roads initiative in Germany, where the city of Hamburg outfitted about 140 roadside stations over 38 km of urban roads to broadcast information such as traffic signal status and road hazard warnings to vehicles[94]. That pilot, showcased during the 2021 ITS World Congress, allowed cars from automakers such as Volkswagen (VW), Audi and others to receive safety alerts in traffic. Similar pilots are underway in other EU cities and corridors, ensuring that Europe's motorways and urban centres will be ready as automakers begin introducing C-V2X NTN capable vehicles on the market.

As vehicle autonomy progresses towards higher levels, the C-V2X standardised framework will be instrumental in creating a resilient, intelligent transportation ecosystem that seamlessly integrates connected vehicles, smart infrastructure, and cloud-based mobility services. It's hybrid architecture, supporting LTE, 5G, and NTN, ensures a smooth transition for both manufacturers and public infrastructure operators.



92 Germany's new CAV testbed in Dusseldorf features Siemens' V2X and ITS equipment | Traffic Technology Today
93 https://5g-ppp.eu/wp-content/uploads/2020/10/5G-for-CCAM-in-Cross-Border-Corridors_5G-PPP-White-Paper-Final2-1.pdf
94 https://www.c-roads.eu/fileadmin/user_upload/media/Dokumente/C-Roads_Brochure_2021_final_2.pdf

5.5 5G NON-TERRESTRIAL NETWORKS

5G non-terrestrial networks represent a critical evolution in automotive connectivity, bridging the coverage gaps inherent in terrestrial networks and ensuring reliable, seamless communication for connected and autonomous vehicles. As vehicles increasingly rely on real-time data exchange for navigation, safety, and operational efficiency, the limitations of existing terrestrial infrastructure, such as network blackspots in rural areas, inconsistent coverage along highways, and roaming restrictions across borders, pose significant challenges. 5G non-terrestrial networks, as defined in 3GPP Release 17 and further refined in Release 18, address these issues by integrating satellite-based communication into the 5G ecosystem, enabling direct and uninterrupted Vehicle-to-Network (V2N) connectivity through LEO satellites. This approach ensures that vehicles maintain high-speed, low-latency connectivity even in environments where terrestrial networks are unreliable or unavailable.[21]

A major challenge in 5G non-terrestrial-networks for automotive applications is network handover and session continuity, particularly when vehicles move between terrestrial and satellite networks. Traditional cellular systems struggle with maintaining persistent connections during rapid handovers, leading to service interruptions that can disrupt critical vehicle functions such as real-time navigation, OTA software updates, and emergency communications.[95]

To overcome this, 5G non-terrestrial network protocols introduce advanced non-terrestrial handover mechanisms (NTHO) that facilitate seamless transitions between terrestrial 5G macro cells and satellite beams. This is achieved through dual-mode user equipment that supports multi-connectivity with both ground-based and space-based networks, ensuring that vehicles remain connected without experiencing session dropouts. Furthermore, adaptive beam handoff mechanisms leverage multi-beam tracking and dynamic beamforming to maintain stable links even as vehicles traverse different network environments.

Given the high orbital velocity of LEO satellites (~7.5 km/s), maintaining precise frequency synchronisation between vehicles and moving satellites presents another significant technical challenge. Real-time Doppler compensation algorithms are implemented within LEO terminal modems to adjust for frequency shifts induced by satellite movement, allowing connected vehicles to sustain reliable data links even when traveling at high speeds on highways or operating in urban environments with dense signal reflections. Additionally, advances in massive MIMO (multiple-input, multiple-output) and hybrid beamforming enable LEO satellites to establish direct-to-vehicle connections, reducing dependency on terrestrial relays and allowing vehicles to communicate directly with space-based networks. This is particularly crucial for applications requiring real-time command and control, OTA software updates, and emergency response services, especially in remote regions where terrestrial infrastructure is sparse or unavailable.[96]

In a technical report produced by 5GAA[97] it is highlighted that the deployment of 5G non-terrestrial networks for automotive applications follows a phased roadmap, aligned with the

95 https://www.all-about-industries.com/5g-network-satellites-autonomous-vehicle-connectivity-a-522458feaf824ead2370181bb9be7ec6/

96 Pal Arora T, Petrunin I, Hill-Valler J, Anyaegbu E. (2024) Improving time transfer performance for low earth orbit satellites. In: 2024 IEEE International Instrumentation and Measurement Technology Conference (I2MTC), 20 - 23 May 2024, Glasgow, United Kingdom

97 https://5gaa.org/maximising-the-benefit-of-future-satellite-communications-for-automotive/

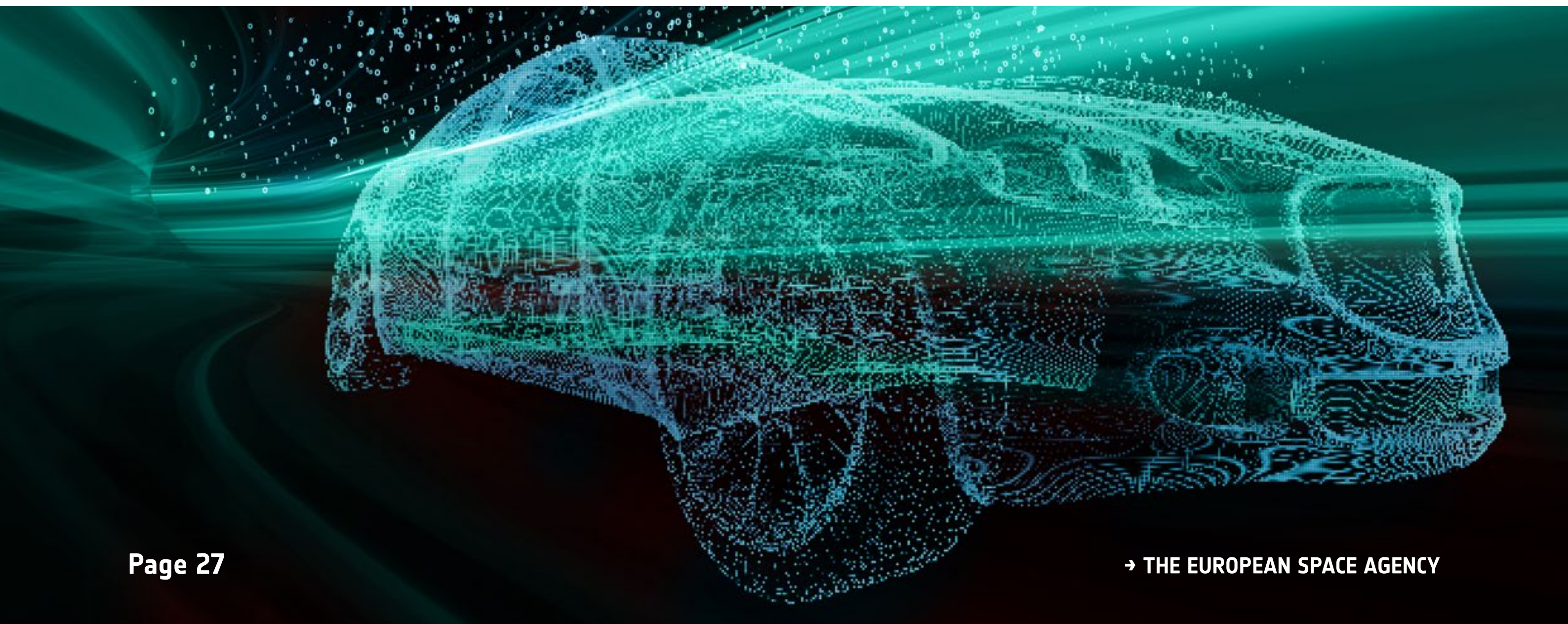
capabilities defined in 3GPP Release 17 and 18. The initial phase, expected to commence by 2027, will introduce narrowband data rate services (<400 kbps), primarily targeting emergency communication and basic safety applications in remote and underserved regions. By 2029, the next phase will enable wideband data rate services (<10 Mbps), facilitating more advanced use cases such as high-definition (HD) map data collection, vehicle telematics, and seamless OTA updates for connected vehicles. Finally, by 2030, broadband data rate services (>10 Mbps) are expected to become commercially viable, allowing for high-throughput applications like 4K video streaming, real-time cloud gaming, and AI-driven autonomous vehicle decision-making. This roadmap underscores the progressive enhancement of non-terrestrial networks capabilities, ensuring that connected and autonomous vehicles can leverage increasingly robust and high-capacity communication channels.[21]

The report goes on to define five main reasons why non-terrestrial networks are perceived as important. The first need originates from the automotive industry's transformation propelled by connectivity. A phased approach is emerging, beginning with essential narrowband applications such as emergency calls, remote vehicle access, and core telematics services. This will progressively evolve to support more data-intensive digital services, including 4K video streaming, cloud-based gaming, immersive Metaverse applications, and fully autonomous driving capabilities. Achieving seamless mobility between terrestrial and non-terrestrial networks is therefore crucial to ensuring continuous service across all geographies.

As a second highlighted reason, terrestrial networks still suffer from coverage gaps – addressable by utilizing non-terrestrial networks. Further, the industry now faces a strategic opportunity to shape future 3GPP releases towards satellite service, some efforts already including non-terrestrial networks thanks to collaborative contributions between 5GAA, the European Space Agency and more industry representatives as extensively discussed in this technical report.

The advent of low-cost LEO satellite mega-constellations is further accelerating the importance of non-terrestrial and terrestrial network harmonisation, enabling broadband access to millions of vehicles and users worldwide. This connectivity revolution is also fundamentally altering automotive business models; as vehicles become "always-on" platforms for digital services, automakers that fail to adopt pervasive connectivity risk obsolescence in an increasingly data-driven and service-centric market.

As 5G non-terrestrial networks adoption accelerates, we at the ESA's Space for 5G/6G programme office invite automakers and telecommunication providers to collaborate towards the integration of satellite connectivity into vehicle platforms, ensuring that future mobility ecosystems can fully capitalise on hybrid satellite-terrestrial networks.



6. CONNECTED MOBILITY USE CASES

6.1 ENABLING THE CAR OF THE FUTURE

Connectivity in automotive is transforming both the satellite communication and the automotive industries, enabling a wide array of use cases that enhance vehicle performance, safety, and user experience. Advanced communication technologies, such as vehicle-to-everything (V2X) connectivity, over-the-air software updates, and cloud-based data analytics, have paved the way for smarter, more efficient mobility solutions. These innovations support further applications such as real-time traffic management, predictive maintenance, remote diagnostics, and enhanced in-vehicle entertainment, significantly improving both individual and fleet operations. As discussed, connectivity is also a key enabler of autonomous driving, smart city integration, and mobility-as-a-service (MaaS) solutions, contributing to a seamless and intelligent transportation ecosystem.

Satellite communications also play a significant role in global supply chain visibility. Providers like Orbcomm[98] and Albedo[99] are equipped to offer satellite-enabled tracking of components and vehicles in transit, even in regions with limited terrestrial coverage. This allows manufacturers to respond more dynamically to disruptions, improving transparency and resilience across global logistics operations.

Infrastructure monitoring is another area where satellite data are proving invaluable. Using Earth Observation (EO) and thermal imaging, companies such as SatVu[100], ICEYE[101], and Planet Labs[102] can provide automotive and government agencies with monitoring of road quality and infrastructure health. These insights feed into smart mobility systems, helping plan predictive maintenance and optimising vehicle routing to reduce wear and tear.

In terms of traffic management, satellites provide vital data links in rural or infrastructure-poor regions. Companies like Teralytics[103], Mapbox[104], and Eutelsat OneWeb[105] are equipped to deliver aggregated mobility and traffic flow analytics via satellite connectivity. This supports more dynamic routing decisions, real-time congestion management, and broader implementation of intelligent transportation systems.

As discussed, satellite communications also prove essential for autonomous driving and teleoperation systems. For example, Xona Space Systems[106] and blackshark.ai[107] are developing satellite-based positioning technologies that offer greater accuracy than traditional GNSS. These systems are being tested with automotive and logistics partners to enable highly precise vehicle navigation.

98 https://www.orbcomm.com/eu
99 https://albedo.com/
100 https://www.satellitevu.com/
101 https://www.iceye.com/
102 https://www.planet.com/
103 https://teralytics.net/
104 https://www.mapbox.com/
105 https://oneweb.net/solutions/land-mobility
106 https://www.xonaspace.com/
107 https://blackshark.ai/

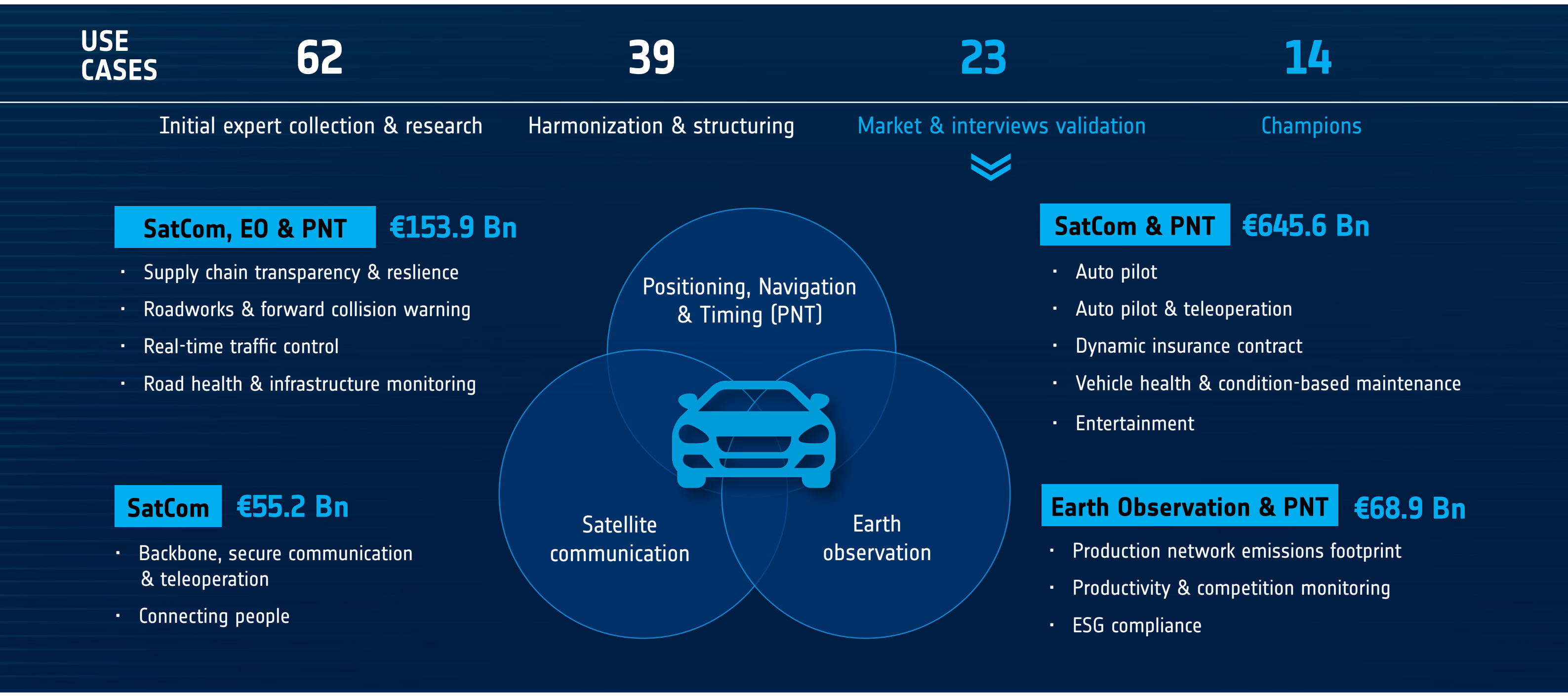


Figure 6: *Automotive use cases down selected according to their financial impact.*

In-vehicle passenger connectivity is another growing application. Satellite broadband providers like Starlink[108] are actively working with automotive OEMs such as Ford, and Tesla to deliver consistent, high-speed internet directly to vehicles.

As developments continue to evolve, the impact of connected mobility is becoming more profound, redefining how vehicles interact with their surroundings and how users engage with transportation services. In a previous edition[109] of this white paper, some use cases related to connected mobility were covered extensively.

Additionally, in an automotive study focusing on space-enabled applications contacted by ESA to a consortium led by Einstein ventures[110] a convergence was defined between software-defined vehicles and next-generation satellite services. The paper[111] goes on to forecast this convergence to cause a €255 billion of direct economic impact in Europe.

As such, satellite communications-enabled applications are not only connectivity enhancements, but they are also foundational to the future digital automotive economy. In Figure 7 from the Einstein study, this impact is visualised across 23 high impact use cases prioritized from 64 total assessed cases, the majority of which carry a satellite communications element.

A broad categorisation of use cases has also been extensively covered in 5GAA's report series C-V2X Use Cases and Service Level Requirements (Vols. I, II and III)[112] and in one of their recent publications — A visionary roadmap for advanced driving use cases, connectivity, and technologies.[113] among other 5GAA publications. A full list of 5GAA's publications[114] is provided for further reading.

One of the most prominent and interesting use cases highlighted by 5GAA that benefits from satellite communications is teleoperated driving. This functionality allows a remote human operator to control or support a vehicle when automated systems are unable to resolve uncertain conditions, such as navigating through snow-covered roads or complex intersections. The need for continuous connectivity to cast control commands, coupled with the need for high reliability makes satellite communications

108 https://www.starlink.com/
109 https://connectivity.esa.int/automotive-white-paper-request
110 https://www.einstein-iv.space/
111 https://www.einstein-iv.space/space-enabled-applications-in-the-automotive-sector
112 https://5gaa.org/c-v2x-use-cases-and-service-level-requirements-2025/
113 https://5gaa.org/content/uploads/2025/01/5gaa-wi-cv2xrm-iii-roadmap-white-paper.pd
114 https://5gaa.org/publications/

indispensable for this use case. The 5GAA Volume II report outlines latency targets ranging from 20 to 200 milliseconds, data rates of up to 32 Mbps for video streaming, and reliability requirements of up to 99.999%, underscoring the rigorous performance standards needed for such scenarios[115].

Automated valet parking, particularly when executed through remote motion guidance, is another application where satellite communications add significant value (when parking outdoor with line of sight to satellites). In cases where a vehicle is directed remotely within a parking facility that is potentially lacking full 5G coverage or any terrestrial connectivity, satellite links can ensure that positioning data and manoeuvring commands are reliably transmitted. According to Volume III of the 5GAA reports[116], this use case demands latency as low as 40 milliseconds for certain control loops and information rates from 0.2 to 2 Mbps.

The need for vehicles to receive software updates is increasingly common and widely discussed within this whitepaper. The first volume of the 5GAA studied use cases[117] discusses this scenario in the context of software maintenance via peer-to-peer or edge node relaying, emphasising the utility of satellite communications in supporting continuous fleet management across geographies.

In addition to safety and operations, infotainment and emergency data transmission represent further domains where satellite communications play a transformative role. In-vehicle entertainment services such as high-definition content streaming require significant bandwidth, which may not always be guaranteed in high-traffic or rural regions. Emergency scenarios such as real-time patient monitoring during ambulance transport — demand guaranteed delivery of telemetry and voice data with reliability exceeding 99.999%. The 5GAA reports indicate video requirements of up to 8 Mbps, health data rates around 1 Mbps, and continuous voice transmission capabilities.

Lastly, satellite communications are pivotal in enabling real-time fleet and vehicle health monitoring in sectors where vehicles operate outside dense urban environments. Modern vehicles rely on uninterrupted telemetry and diagnostics to ensure predictive maintenance and avoid system failures. The use case descriptions from Volume I confirm the necessity for continuous data synchronisation and real-time health status communication, both of which are supported by the global reach and stability of SATCOM infrastructure.

Together, these and more emerging use cases satellite communications as a necessary technological milestone for the future of connected and automated vehicles. By bridging the coverage gaps of terrestrial systems and providing a redundant, high-performance communication layer, satellite networks not only enhance safety and efficiency but also support the scalable deployment of advanced mobility solutions.

115 5gaa-c-v2x-use-cases-and-service-level-requirements-vol-ii-v2.0.pdf
116 5gaa-tr-cv2x-use-cases-and-service-level-requirements-vol-iii.pdf
117 5gaa-c-v2x-use-cases-and-service-level-requirements-vol-i-v2.0.pdf

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