

# Vehicular Communication Systems: Enabling Technologies, Applications, and Future Outlook on Intelligent Transportation

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## ABSTRACT

Numerous technologies have been deployed to assist and manage transportation. But recent concerted efforts in academia and industry point to a paradigm shift in intelligent transportation systems. Vehicles will carry computing and communication platforms, and will have enhanced sensing capabilities. They will enable new versatile systems that enhance transportation safety and efficiency and will provide infotainment. This article surveys the state-of-the-art approaches, solutions, and technologies across a broad range of projects for vehicular communication systems.

## INTRODUCTION

The growing mobility of people and goods incurs high societal costs: traffic congestion, fatalities and injuries. In the past decade, numerous efforts have sought to mitigate these problems and produced solutions we currently use, for example: information on traffic and hazardous situations are broadcast via the FM radio band, temporarily interrupting the user-tuned reception; variable message signs, spaced a few kilometers apart or at strategic points (e.g., merging highways, tunnels, bridges) along freeways, warn drivers about changing conditions; electronic toll systems collect fees with reduced or almost no disruption of traffic flow.

At the same time, vehicles have increasingly effective driver assistance and protection mechanisms. Various onboard controls and information sources allow the driver to customize her driving experience and remain up to date on the vehicle status; passive safety mechanisms protect the passengers and the vehicle against adverse driving conditions (e.g., anti-lock braking systems); navigation systems, compasses, rear and front parking radars, and cameras are the most

common among autonomous sensor technologies. They perceive the landscape, road, and vehicle location, and capture in real time the vehicle surroundings and traffic situation to appropriately warn the driver and either prevent accidents or at least reduce their effects. Beyond these technologies, relying on heterogeneous technologies (e.g., roadside cameras), more complex systems enable fleet management and the collection of traffic information.

Recent technological developments, notably in mobile computing, wireless communication, and remote sensing, are now pushing intelligent transportation systems (ITS) toward a major leap forward. Vehicles are already sophisticated computing systems, with several computers and sensors onboard, each dedicated to one part of the car operation. The new element is the addition of new wireless communication, computing and sensing capabilities. Interconnected vehicles not only collect information about themselves and their environment, but they also exchange this information in real time with other nearby (in principle) vehicles.

To put it simply, radio-communication-based solutions can operate beyond the line-of-sight constraints of radar and vision solutions, and they can enable cooperative approaches. Vehicles and infrastructure cooperate to perceive potentially dangerous situations in an extended space and time horizon. Appropriate vehicular communication (VC) architectures are necessary to create reliable and extended driving support systems for road safety and transportation efficiency.

This article contributes a survey of VC systems, covering the developments of the past few years. We cover the state of the art, and we distill the technical details from a wide range of research and development projects. Rather than an architectural view alone, we seek to capture concisely and quantitatively the most up-to-date understanding in industry and academia.

We first provide an overview of VC systems and their role in intelligent transportation systems, along with a summary of the related major activities to date. Then we present onboard equipment, the VC wireless data link technologies, the VC networking protocols, and the VC-enabled applications. We conclude with a discussion of the next steps in the evolution of VC systems.

## OVERVIEW

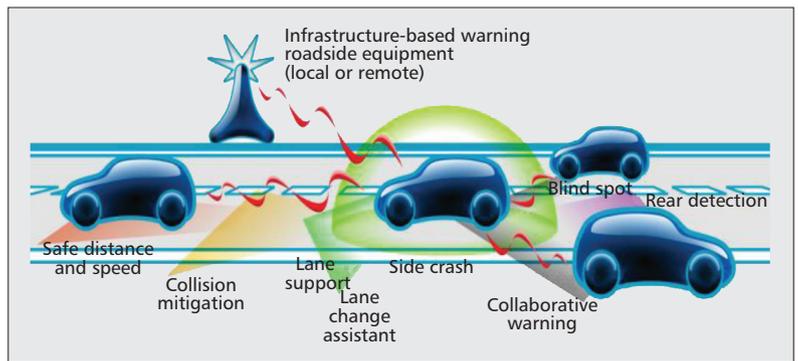
Vehicles will be equipped with novel *computing*, *communication*, and *sensing capabilities*, and *user interfaces*. These will support a spectrum of applications that enhance *transportation safety and efficiency*, but also provide new or integrate existing services for drivers and passengers. A significant role is envisioned for existing or upcoming wireless infrastructure (e.g., cellular), connectivity to the wireline part of the Internet, and dedicated roadside infrastructure units (RSUs). User-portable devices are also expected to be wirelessly attached to the onboard equipment.

A key aspect of VC systems is to expand the time horizon of information relevant to driving safety and transportation efficiency, introduce new information sources, and improve its quality. The basis is a *collaborative approach*, with each vehicle and RSU contributing relevant information, as illustrated in Fig. 1: based on their own sensing and on information received from nearby peers and RSUs, vehicles can anticipate, detect, and avoid dangerous or unwanted situations. For example, timely notifications about lane changes, emergency braking, and unsafely approaching vehicles can be highly beneficial. The same is true for notifications about dangerous or heavy traffic conditions disseminated by RSUs, locally or within a larger region with the help of other vehicles.

The development of such VC systems and related technologies has been the subject of numerous projects around the globe, as well as for standardization working groups and industrial consortia. We summarize the large majority of such recent efforts in Table 1, with projects having complementary but often similar objectives and approaches. The table summarizes the objectives of each project, consortium, or initiative, along with its duration and context.

This multitude of concerted efforts and approaches indicates the need for coordination. Cooperative system projects in Europe, notably those represented in the *COMeSafety* initiative, have converged on a common reference architecture, shown in Fig. 2, with direct involvement from the European Telecommunications Standards Institute (ETSI) TC ITS and the International Organization for Standards (ISO) TC204 WG16 (ITS Communications). It has therefore been adopted quite widely in Europe, and in several cases outside Europe. The architecture is described in [1], and a concise survey is given in [2].

Simply speaking, wireless transmission and medium access technologies adapted to the VC environment are the primary enabling technology. Conceptually, on top of them, networking



**Figure 1.** Illustration of VC system functionality. Safety applications leverage on vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communication, to extend the driver's horizon and offer early detection of perilous situations and notify the driver accordingly. It is currently debated whether some automated control action should be taken in future systems, for example, to ensure the avoidance of a collision without the intervention of the driver.

technologies allow for data exchange among nearby and remote devices (vehicles, RSUs, and other servers). They, in turn, support the aforementioned range of applications, with the mediation of a range of facilities, that is, functionality that extracts data (mostly location- and time-stamped) from the network operation and establishes sessions between two VC system entities when necessary. The basic system entity is an ITS station, which can be composed of a router and a host, or be a single-box implementation that covers all functions. One example is the top-level architecture of the CVIS project shown in Fig. 3.

## ONBOARD EQUIPMENT

The VC computing, communication, and sensing equipment and user interfaces will be, in most cases, new with respect to the current onboard equipment. In terms of sensing and user interface hardware and software, VC systems will leverage on the array of equipment vehicles currently carry; for example, data concerning the vehicle operation will be obtained via the corresponding or upgraded onboard interfaces. In general, VC technology will not be developed from scratch; rather, as ongoing projects show, mature and well understood components and their variants will be the basis. In the rest of this section we outline the characteristics of the onboard equipment as it is currently developed and integrated.

*VC computing platforms* are to be dedicated to VC functionality. Recall that cars are already equipped with multiple processors and micro-controllers dedicated to tasks such as fuel injection, braking, transmission, and battery charging; for easy reference, we term these *car processors and controllers*. The VC computing platform(s) will be functionally independent and responsible for running the vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communication protocols and the supported applications.

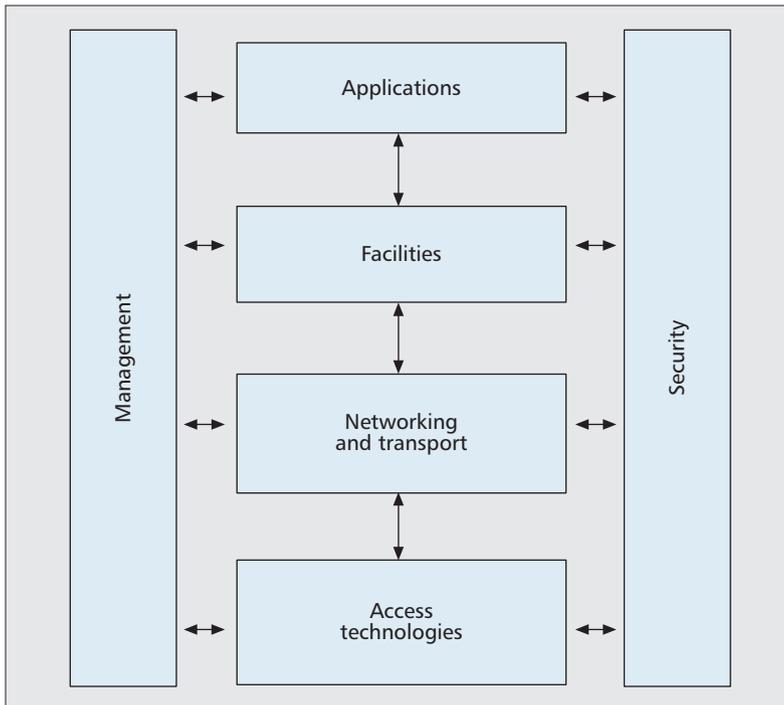
The current approach is to use commercial off-the-shelf computing technology with good performance and flexible interfaces. There are differences with existing desktop and laptop

| Project name                                 | Project information |  |  |
|--|---------------------|--|--|
|  | Period              | External funding                             | Brief description of objectives  |
| AKTIV  | 2006–2010           | Ministry of Economics and Technology Germany | Design, development, and evaluation of driver assistance systems, knowledge and information technologies, efficient traffic management, and V2V and V2I communication; <a href="http://www.aktiv-online.org/index.html">http://www.aktiv-online.org/index.html</a>                                   |
| Car to Car Communication Consortium (C2C-CC) | Ongoing             | N/A  | Development of a European industry standard for VC communication systems, active safety applications prototyping and demonstrations, harmonization of VC standards worldwide, realistic deployment strategies and business models; <a href="http://www.car-2-car.org/">http://www.car-2-car.org/</a> |
| CityMobil                                    | 2006–2010           | European Union                               | Integration of automated transport systems in the urban environment, based on real-life implementations; <a href="http://www.citymobil-project.eu/">http://www.citymobil-project.eu/</a>   |
| COM2REACT                                    | 2007–2008           | European Union                               | Distributed traffic application, based on cellular and V2V communication, in-car and V2V communication systems, vehicle-to-center communication; <a href="http://www.com2react-project.org/">http://www.com2react-project.org/</a>   |
| COOPERS                                      | 2006–2010           | European Union                               | Telematic applications for the road infrastructure, cooperative traffic management involving vehicles and roadside infrastructure; <a href="http://www.coopers-ip.eu/">http://www.coopers-ip.eu/</a>   |
| CVIS   | 2007–2011           | European Union                               | Multichannel terminal capable of continuous Internet connection, open communication architecture, enhanced positioning, commercial applications, toolkit (models, guidelines, and recommendations), and deployment roadmaps; <a href="http://www.cvisproject.org/">http://www.cvisproject.org/</a>   |
| CyberCars2                                   | 2006–2008           | European Union                               | Cooperation between vehicles running at close range (platooning) and at intersections (merging, crossing); <a href="http://www.cybercars.org">http://www.cybercars.org</a>   |
| CyberMove                                    | 2001–2004           | European Union                               | Investigation toward new transportation systems based on CyberCars (automated vehicles) as a complement to public mass transportation; <a href="http://www.cybermove.org">http://www.cybermove.org</a>   |
| ETSI TC ITS                                  | Ongoing             | N/A  | Standardization activities to support the development and implementation of intelligent transportation systems; <a href="http://portal.etsi.org/Portal_Common/home.asp">http://portal.etsi.org/Portal_Common/home.asp</a>  |
| EVITA  | 2008–2011           | European Union                               | Secure and trustworthy intravehicular communication; architecture for automotive onboard networks to thwart tampering and protect sensitive data inside a vehicle; <a href="http://evita-project.org/">http://evita-project.org/</a>   |
| GeoNet                                       | 2008–2009           | European Union                               | Specifying, developing and testing IPv6 geo-networking that can be used within a cooperative architecture (e.g., CVIS); <a href="http://www.geonet-project.eu/">http://www.geonet-project.eu/</a>  |
| HAVE-IT                                      | 2008–2011           | European Union                               | Automated merging, queue assistance, temporary auto-pilot, and active green driving mechanisms, integrated in six demonstrator vehicles; <a href="http://www.haveit-eu.org">http://www.haveit-eu.org</a>   |

Table 1 continued on next page....

| Project name  | Project information  |   |  |
|---|----------------------|---|--|
|   | Period               | External funding  | Brief description of objectives  |
| IEEE P1609  | Ongoing              | N/A   | Standard for wireless access in vehicular environments (WAVE) — Resource manager, physical and medium access control, security services, networking services, multichannel operations for V2V and V2I communication; <a href="http://www.standards.its.dot.gov/fact_sheet.asp?f=80">http://www.standards.its.dot.gov/fact_sheet.asp?f=80</a> |
| ISO TC 204 WG16/CALM  | Ongoing              | N/A   | Standardized set of air interface protocols and parameters for medium- and long-range high-speed ITS communication, across several media, networking, and upper layer protocols; <a href="http://www.isotc204wg16.org/">http://www.isotc204wg16.org/</a>   |
| NoW: Network on Wheels  | 2004–2008            | Ministry of Education and Research Germany                    | Protocols and data security algorithms for V2V/V2I communication, active safety scenario, V2I electronic payment, introduction strategies, and business models; <a href="http://www.network-on-wheels.de/">http://www.network-on-wheels.de/</a>  |
| PATH  | Ongoing              | California Department of Transportation (CalTrans)            | Multidisciplinary research program administered by the UC Berkeley Institute of Transportation Studies and CalTrans; activities in four areas: policy and behavioral, transportation safety, and traffic and transit operations research; <a href="http://www.path.berkeley.edu/">http://www.path.berkeley.edu/</a>                          |
| SAFESPOT  | 2006–2010            | European Union  | Ad hoc networking, accurate relative localization, dynamic local traffic maps; scenario-based evaluation of safety applications; sustainable deployment strategy; <a href="http://www.safespot-eu.org/">http://www.safespot-eu.org/</a>  |
| SEVECOM   | 2006–2009            | European Union  | Security architecture for vehicular communication systems; identity management, security and privacy-enhancing mechanisms and protocols; in-car protection; data consistency; system performance evaluation; demonstration; <a href="http://www.sevecom.com">http://www.sevecom.com</a>  |
| SmartWay  | 2006–2010            | Ministry of Land, Infrastructure, Transport and Tourism Japan | Driving safety support systems based on vehicle–highway cooperation; <a href="http://www.mlit.go.jp/road/ITS/">http://www.mlit.go.jp/road/ITS/</a>   |
| IntelliDrive<br>Previously known as the VII consortium (VIIC) | Ongoing<br>2005–2008 | Department of Transportation USA                              | Initiative of the ITS Joint Programs Office (JPO) at the DoT's Research and Innovative Technology Administration (RITA) VC technologies and applications, V2V, V2I, mobility, and policy research; <a href="http://www.intellidriveusa.org/">http://www.intellidriveusa.org/</a>   |
| VSC   | 2002–2004            | Department of Transportation USA                              | DSRC demonstration and safety beaconing for V2V and V2I communication  |
| CAMP/VSC-2  | 2005–2009            | Department of Transportation USA                              | Cooperative Intersection Collision Avoidance System — Violations (CICAS-V); Emergency Electronic Brake Lights (EEBL); Vehicle Safety Communications — Applications (VSC-A)   |

**Table 1.** Summary information on representative VC projects, consortia, and working groups.



**Figure 2.** Common reference architecture for cooperative vehicular communication systems, as agreed primarily among European projects.

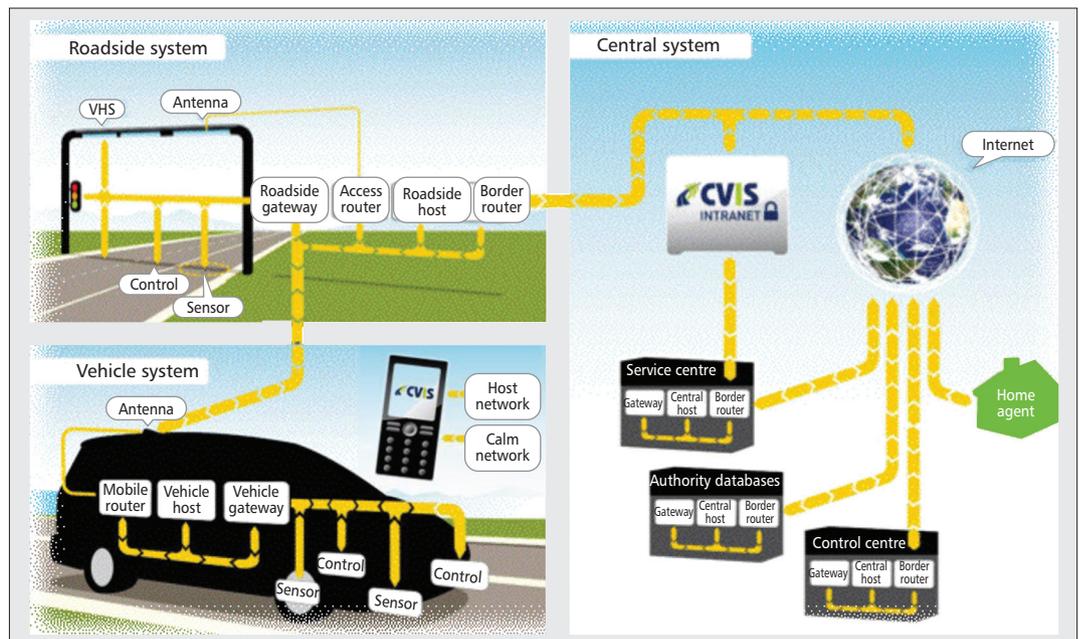
machines: *Car PCs* have relatively *hardened hardware* and *adapted packaging* so that operation is possible in a wider range of conditions and according to the VC constraints. In addition, car PCs have the appropriate interface to the rest of the in-vehicle information system, which is essentially the control area network (CAN) or other technology (e.g., LIN, MOST, or Flexray) that interconnects car processors and controllers [3].

Figure 4 illustrates one approach along these lines, as developed by the CVIS project. Rather than having one car PC, there are two boxes: one performing all networking operations and acting as the interface to the car processors and sensors (termed the *mobile router*), and one doing all the computing for the VC applications and the user interface (termed the *mobile host*). The mobile router integrates a special-purpose card that integrates sensors and resolves, at the hardware level, time-critical tasks such as the real-time acquisition of location and time and synchronization. The use of two boxes appears in other projects too (e.g., the COM2REACT platform).

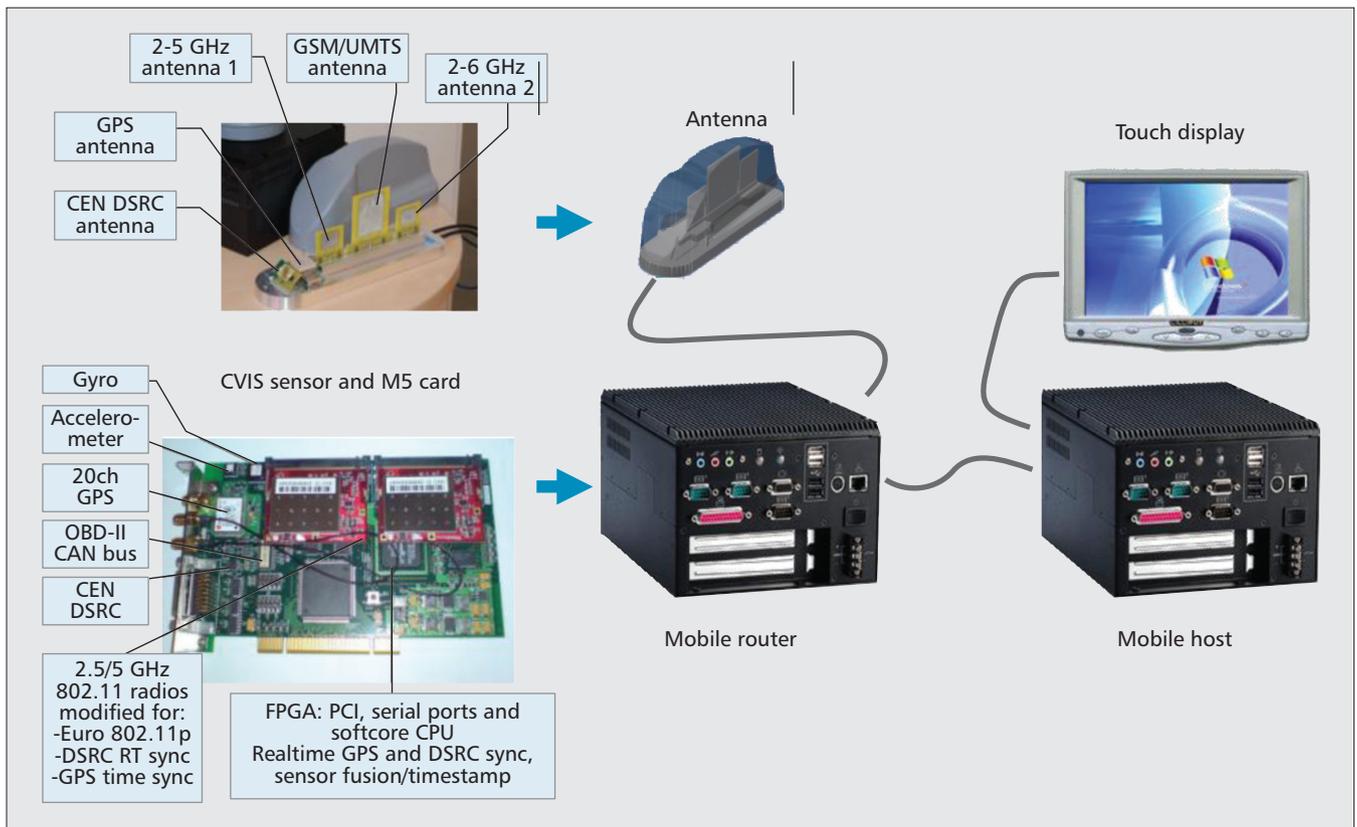
*Sensing equipment* is already installed onboard; thus, a CAN gateway is present to obtain data from onboard sensors, typically velocity, direction, temperature, airbag status, rear and front cameras, parking assistance radars, and so on. At the same time, global navigation satellite systems (GNSS) such as the Global Positioning System (GPS) can also be integrated, along with other advanced systems, such as collision warning or advanced cruise control radars.

The accuracy of location and time depends on the GPS receiver and its signal processing capabilities. For example, small-footprint receivers can achieve 10–15 ns synchronization and localization errors of 6–30 m. There are other GNSS solutions, such as the Russian counterpart of GPS that is compatible with the U.S.-built GPS, and the upcoming European Galileo system (currently with one operational satellite while the rest of the constellation is being deployed).

The COM2REACT project integrated a CAN gateway, a GPS, a camera, and ultrasound transceivers. The CVIS project developed a special sensor card (mentioned above as part of the



**Figure 3.** System architectural view, as per the CVIS approach. Roadside and onboard equipment communicate; the roadside equipment provides access to information stored in a number of databases and servers related to the VC system, but also to the user's home equipment through mobile IPv6 connectivity.



**Figure 4.** Onboard vehicular communication (VC) system equipment: computing platforms (mobile router and mobile host); communication equipment, with multiple wireless data links (e.g., 802.11p, cellular) and broadcast receivers (e.g., GPS); sensors; and in-vehicle user interface.

mobile router PC). The card provides GPS data for accurate time and position, an inertial sensor package with gyroscope and accelerometers, and an interface to the vehicle CAN-bus. The provided real-time processing and time stamping is important for the networking and application protocols described later in this article. Similar efforts, in terms of extracting information safety-related sensory measurements from the in-vehicle system, are undertaken by SAFEPROBE, a subproject of SAFESPOT.

The communication equipment comprises a set of technologies with different characteristics (bit rates, communication range, transmission power, frequency bands). Basically, there is *short-range ad hoc communication* to enable primarily V2V but also V2I communication, and *long-range infrastructure-based communication* primarily for V2I purposes. Finally, there is the option of integrating additional long-range broadband transceivers, including broadcast receivers.

The basis of VC systems is a variant of the widely known Wi-Fi technology, the IEEE 802.11p protocol [4]. The corresponding transceivers provide for a wireless data link, discussed in the next section, as the basis of the short-range ad hoc communication. Cellular data transceivers provide for long-range communication: typically, Global System for Mobile Communications (GSM)-based General Packet Radio Service (GPRS) transceivers, as well as third-generation Universal Mobile Telecommunications System (UMTS) transceivers. Moreover,

dedicated transceivers (e.g., for deployed toll collection systems — dedicated short-range communication [DSRC]) can also be present.

The frequency allocation for this communication equipment can differ from continent to continent and possibly from country to country. Regarding the newly introduced 802.11p, also known as the encompassing effort of WAVE and the related IEEE 1609 working group activities, there are specific bands allocated for V2V and V2I communication.

The CVIS platform (Fig. 4) has GSM and UMTS interfaces, a dedicated DSRC transceiver, a GSM/UMTS transceiver supporting all data modes, and short-range 802.11p radios that are synchronized with European DSRC toll collection systems. The 802.11p radios offer communication (in the European 5.9 GHz band) along with the previous versions of the protocol (i.e., IEEE 802.11 a/b/g), and an implementation of the IEEE 1609 stack and support for parallel protocol stacks (based on the CALM architecture). Similarly, SAFESPOT builds on the IEEE 802.11p radios and looks into possible integration of other technologies (cellular or infrared communication); COM2REACT used Wi-Fi 802.11b with GPRS.

## WIRELESS DATA LINK

As explained earlier, vehicles are envisioned to carry multiple types of wireless transceivers; that is, each vehicle will be able to communicate across more than one wireless data links. Each

| Indicative wireless data link characteristics | Technology                   |                                     |  |                       |
|---|------------------------------|-------------------------------------|--|-----------------------|
|   | 802.11p WAVE                 | Wi-Fi                               | Cellular                                 | Infrared              |
| Bit rate                                      | 3–27 Mb/s                    | 6–54 Mb/s                           | < 2 Mb/s                                 | < 1 Mb/s<br>< 2 Mb/s  |
| Communication range*                          | < 1000 m                     | < 100 m                             | < 15 km                                  | < 100 m (CALM IR)     |
| Transmission power for mobile (maximum)       | 760 mW (US)<br>2 W EIRP (EU) | 100 mW                              | 2000 mW (GSM)<br>380 mW (UMTS)           | 12800 W/Sr pulse peak |
| Channel bandwidth                             | 10 MHz<br>20 MHz             | 1–40 MHz                            | 25 MHz (GSM)<br>60 MHz (UMTS)            | N/A (optical carrier) |
| Allocated spectrum                            | 75 MHz (US)<br>30 MHz (EU)   | 50 MHz @ 2.5 GHz<br>300 MHz @ 5 GHz | (Operator-dependent)                     | N/A (optical carrier) |
| Suitability for mobility                      | High                         | Low                                 | High                                     | Medium                |
| Frequency band(s)                             | 5.86–5.92 GHz                | 2.4 GHz, 5.2 GHz                    | 800 MHz, 900 MHz<br>1800 MHz<br>1900 MHz | 835–1035 nm           |
| Standards                                     | IEEE, ISO, ETSI              | IEEE                                | ETSI, 3GPP                               | ISO                   |

\*The communication range depends on parameters such as data rate, power, bandwidth, and topography; values given in this table are estimates and may vary.

**Table 2.** Summary information on representative VC wireless data links.

of them provides a physical layer, the implementation of methods to transmit and receive data (symbols representing bit sequences) across the airwaves, and a medium access control layer, protocols that regulate how collocated transceivers access (i.e., transmit and receive across) the wireless medium, in order to reduce the chance of or avoid collisions (transmissions overlapping in frequency and/or time).

In Table 2, we summarize indicative values for a set of characteristics of and information on the main wireless data links currently developed and integrated in automotive systems. Beyond operational characteristics (e.g., bit rate, range, bandwidth), we also point out which standards pertain to each technology. Interested readers are referred to the documentation of the corresponding standardization bodies for more information.

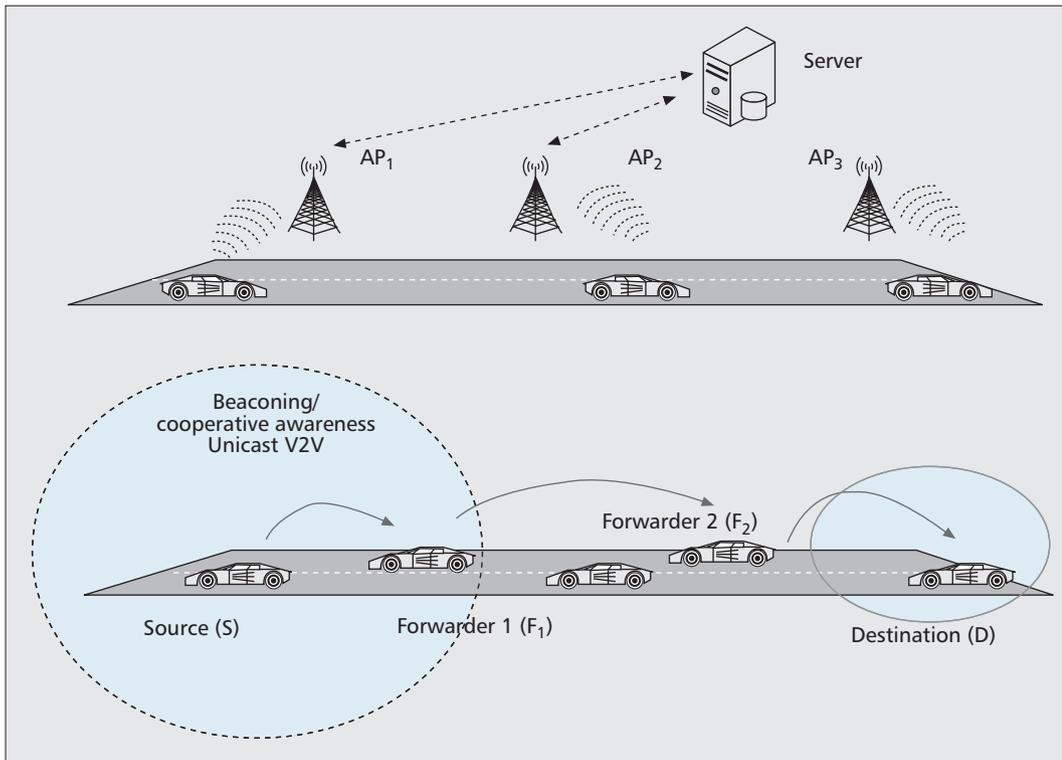
An important aspect, medium access control latency, is not listed in the table as it depends greatly on the implemented system and context. Infrastructure-based communication may require delays on the order of seconds, including the association of a mobile transceiver with an infrastructure element, and the registration with the network that grants access rights; this may be, for example, the case for Wi-Fi and cellular systems. Nonetheless, customized implementations of 802.11-based systems allow for very fast association with a Wi-Fi access point, while fast handover techniques allow cellular systems to service nodes moving fast from one base station to another. For transportation safety applications, low-latency communication with neighboring devices is critical; this favors direct V2V communication through a simple medium access control protocol.

The prominent wireless data link for VC is a variant of IEEE 802.11, 802.11p. This specifies physical and medium access control protocols designed with the highly volatile vehicular environment in mind. The operation across multiple channels is specified in IEEE 1609.4. These two elements, combined with a resource manager for the onboard equipment, and specifications of addressing, networking, and security services, are known collectively as the *WAVE* standard; for a recent tutorial, see [5].

## NETWORKING PROTOCOLS

Beaconing is a simple mechanism, used in scores of other networks, to periodically transmit short messages (i.e., a one-hop or local broadcast). Beacons have a special role in VC systems: they provide the identity and rich information on the transmitting vehicle (e.g., location, heading, and other status information) with typical size on the order of 100 bytes. They are transmitted at high frequencies (e.g., 10 times per second) by each vehicle and in an uncoordinated manner. They are the backbone of the cooperative awareness and other transportation safety applications discussed in the next section.

Beacons are transmitted across the 802.11p/WAVE data link and are typically handled as broadcast packets at the medium access control layer. Beaconing can also be event-driven local broadcasts, perhaps repeated for a protocol-specific period (e.g., a safety-related warning triggered by an in-vehicle event). Safety-related beacons must arrive at neighbor nodes within a specific maximum



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**Figure 5.** Illustration of networking protocols for VC systems. Top: Internet connectivity via roadside and other infrastructure, and vehicle-to-infrastructure communication; bottom: vehicle-to-vehicle communication, for communication with neighboring devices (directly reachable vehicles and roadside infrastructure), as well as devices across multiple hops and geographically remote.

delay, and their reception should be possible with minimum reliability, as per the application requirements.

At this point, VC implementations do not attempt reliable broadcast, but rather take very simple best effort approaches that rely on redundant transmissions. Under highly congested settings, with 100 vehicles within range, the reception reliability can be rather low (e.g., 60 percent of transmitted beacons); however, each vehicle transmits a beacon every 10 ms, so within a fraction of second, even after several lost beacons, reception is possible.

*Flooding* is the natural extension of beaconing across multiple wireless hops. Packets specify a time to live (i.e., a number of hops to be relayed across), or their type and content allow receivers to determine whether to rebroadcast them. Eventually, flooded packets are removed from the network after covering (approximately) the intended area. As it is the initial sender's information that is essential, the relaying nodes of packets flooded in a controlled manner do not need to modify them. This implies that their size as they propagate across the network would not increase. The same would be true if nodes performed some sort of aggregation, with relaying nodes adding, for example, their measurement to an average or a maximum or minimum of the values of nodes involved in protocol execution.

*GeoCast* or *position-based routing* assumes that every node knows its geographical position (e.g., by GPS) and maintains a location table with the geographical positions of other nodes as soft state. Individual nodes can be addressed

based on their geographical location, and a group of nodes can be designated as receivers within a geographical region. Such functionality, also investigated in the more abstract context of ad hoc networks, fits naturally into VC systems:

- Vehicles are already integrating navigation systems (e.g., GPS), and are expected to be location-aware.
- Many transportation safety and efficiency applications are location-specific.

VC is, in fact, closer to GeoCast than to the usual Internet unicast [6].

The choice of a geographic region as a destination for a message is clearly independent of the size of the network (i.e., the number of vehicles present). Individual vehicle addressing, which requires sufficiently accurate knowledge of the destination location, is expected to be a small fraction of the overall traffic. These two aspects indicate that appropriate GeoCast protocols could remain efficient as the scale of VC systems grows.

The basic components of GeoCast are:

- *Beaconing*, for *discovery of neighbors* and their locations
- *A location service*, which can be queried to provide the location of individual nodes
- *Position-based forwarding* toward a given destination (geographic location in general, which can be narrow or broad in region)

The *maintenance of a neighborhood* — information on the set of other vehicles and roadside units within range, along with position and all other relevant information — can be done in various ways. For example, unreliable links can

VC systems will enable applications in three primary directions: transportation safety, transportation efficiency, and user services delivered to the vehicle. The first two categories are the main two drivers for the development of the new systems.

be disregarded (e.g., if a vehicle appears to move relatively fast with respect to a sender, or the data link reports a high number of retries), or neighbors are nodes that appear more relevant (i.e., have the same heading, e.g., are in the same highway flow).

The goal of the location service is to resolve the identity of a vehicle to its current position. This could be done with the help of a facility that maintains locations of vehicles that need to be individually addressed. The instantiation of such a facility can be based on the infrastructure (which can be reached across one or more wireless hops), or done in a peer to peer manner with the locations distributed across nodes. Access to such a facility or possibly to the sought vehicle can be done with a traditional query: a packet is flooded in a controlled manner, requesting the destination, with any authorized and knowledgeable node (RSU or vehicle) responding with the required location information. Location queries and responses are small-size packets, at most the same size as beacons, at on the order of 100 bytes.

Position-based forwarding relays each packet from its source to the destination location, based with individual decisions made at each relaying node based on knowledge about the neighborhood. The objective is to get the packet to approach the destination at each relaying step: the source and each relay choose the next hop that is closest to the destination. This is the basic idea of greedy forwarding, which under some circumstances can be ineffective: there may be no next hop closest to the destination, and in that case a *gap avoidance* algorithm is invoked. Once the packet is in the destination region, nodes within the region locally broadcast the packet. As these are data packets, their payload can be on the order of several hundreds of bytes. Their control overhead (i.e., their headers) does not need to grow with the size of the network; they only need to specify the destination, used by all relaying nodes, and the next hop.

The Car-2-Car Communication Consortium (C2C-CC) has invested significant efforts on the specification of car-to-car communication mechanisms suitable for safety applications, including geonetworking (or GeoCast). GeoNet is a European Union funded project that aims at ensuring convergence between IPv6 and proprietary geonetworking protocols, particularly C2C-CC's geonetworking (Fig. 5).

Connectivity with the Internet is in general required, and it can be achieved with the vehicle establishing sessions with Wi-Fi access points when in range and down- or uploading possibly large volumes of data within a short period of time, notably during contact with (i.e., the period of being in range of) an access point. Of course, Internet connectivity can also be achieved via the cellular GSM/GPRS or UTMS systems, which already have very high coverage. Internet connectivity can be infrequent to support various VC-specific transactions and tasks, but it could also be established, independent of transportation-related issues, for infotainment.

Ongoing projects such as CVIS are developing a communication architecture that relies on the maintenance of constant access to the Internet over IPv6. GeoNet ensures convergence

between geonetworking and IPv6. The goal of GeoNet is to implement and formally test a geonetworking mechanism as a standalone software module that can be incorporated into cooperative systems. GeoNet is very active in standardization and will integrate its module into the CVIS platform so that future projects on cooperative systems can maintain their focus on architecture design, application development, and field trials.

## APPLICATIONS

VC systems will enable applications in three primary directions: transportation safety, transportation efficiency, and user services delivered to the vehicle. The first two categories are the main two drivers for the development of the new systems. The third category leverages on the newly coined and existing systems; in many cases it can naturally blend into the VC and ITS contexts, and can act as a market driving force.

Projects, standardization bodies, and consortia around the globe have been working on the design and development of applications for VC systems. Long lists of applications were initially compiled, projecting into future technologies but also drawing on existing transportation requirements and functionality, looking into how VCs can undertake and enhance support for those. The vast majority of applications fall largely in the above-mentioned three categories:

- The driver is assisted, in order to enhance transportation safety.
- Data, most often region-specific, about the transportation system and traffic conditions are made available to drivers to enhance transportation efficiency.
- Services enhance the users' (passengers and drivers) comfort and ability to perform personal and business transactions while in the vehicle.

In Table 3 we provide a representative list of applications from these three categories. Names do not exactly match those used in each and every project, but rather they are closely compatible with those used by many projects and consortia (e.g., C2C-CC, VSC-A), standardization efforts (e.g., ETSI, IEEE), as well as those broadly used (e.g., SAFESPOT, CVIS, COM2REACT, SEVECOM).

We provide a list of five pieces of information for each application:

- *Communication*, which determines the wireless data link needed, with ad hoc and infrastructure-based referring earlier in the article
- *Messaging type*, which specifies whether the transmission is periodic, event-triggered, limited over a short period, and so on
- *Message period*, applicable to periodic messaging applications
- *Critical latency*, the maximum delay the application requires from the underlying protocol stack to handle and transmit the message
- *Other requirements*, such as the priority at the medium access control layer, the accuracy of positioning, maximum recommended communication range, and so on

|    | Application name                      | Application information  |  |                |         |  |
|----|---------------------------------------|--|--|----------------|---------|--|
|    |                                       | Communication  | Messaging type                               | Message period | Latency | Other requirements   |
| 1  | Emergency Electronic Brake Lights     | Ad hoc V2V   | Event-triggered, time-limited broadcast      | 100 ms         | 100 ms  | Range: 300 m, high priority  |
| 2  | Slow Vehicle Warning                  | Ad hoc V2V   | Periodic permanent broadcast                 | 500 ms         | 100 ms  | High priority  |
| 3  | Intersection Collision Warning        | Ad hoc, infrastructure V2V, V2I                                    | Periodic permanent broadcast                 | 100 ms         | 100 ms  | Accurate positioning on a digital map, high priority                 |
| 4  | Hazardous Location Warning            | Ad hoc, infrastructure I2V, V2V                                    | Event-triggered time-limited GeoCast         | 100 ms         | 100 ms  | High priority  |
| 5  | Traffic Signal Violation Warning      | Ad hoc, infrastructure I2V   | Event-triggered time-limited broadcast       | 100 ms         | 100 ms  | Range: 250 m, High priority  |
| 6  | Pre-Crash Sensing                     | Ad hoc V2V   | Periodic broadcast, unicast                  | 100 ms         | 50 ms   | Range: 50 m, high/mid priority for beaconing/unicast                 |
| 7  | Lane Change Warning                   | Ad hoc V2V   | Periodic broadcast                           | 100 ms         | 100 ms  | Relative positioning accuracy: < 2 m; range: 150 m                   |
| 8  | Cooperative Forward Collision Warning | Ad hoc V2V   | Periodic, event-triggered broadcast, unicast | 100 ms         | 100 ms  | Relative positioning accuracy: < 1 m; range: 150 m                   |
| 9  | Intersection Management               | Infrastructure, ad hoc V2I, V2V                                    | Periodic broadcast, unicast                  | 1000 ms        | 500 ms  | Positioning accuracy: < 5 m  |
| 10 | Limited Access and Detour Warning     | Infrastructure, I2V, other broadcast network                       | Periodic Broadcast                           | 100 ms         | 500 ms  | Mid/low priority   |
| 11 | Cooperative Adaptive Cruise Control   | Ad hoc V2V   | Unicast broadcast                            | 500 ms         | 100 m   | Mid priority   |
| 12 | Electronic Toll Collect               | Infrastructure, ad hoc V2I, cellular                               | Periodic broadcast, unicast                  | 1000 ms        | 200 ms  | CEN DSRC   |
| 13 | Remote Diagnosis/JIT Repair Warning   | Infrastructure, ad hoc V2I, V2V, cellular                          | Unicast, broadcast, event-triggered          | N/A            | 500 ms  | Internet access<br>Service availability                              |
| 14 | Media Download                        | Infrastructure; cellular, other broadcast network                  | Unicast, broadcast, on-demand                | N/A            | 500 ms  | Internet access<br>Digital rights management                         |
| 15 | Map Download/Update                   | Infrastructure, ad hoc V2I, V2V, cellular, other broadcast network | Unicast, broadcast, on-demand                | 1000 ms        | 500 ms  | Internet access<br>Digital rights management<br>Service availability |
| 16 | Ecological Drive Assistance           | Infrastructure, ad hoc V2I, V2V, cellular                          | Unicast, broadcast, on-demand                | 1000 ms        | 500 ms  | Internet access<br>Service availability                              |

**Table 3.** VC-enabled applications and their characteristics.

Among hundreds of use cases, we chose here a subset of applications to illustrate differing requirements. We do not propose values for each application, but rather reflect the content of various technical reports. We refer the interested reader to the deliverables of all the above mentioned projects, and the technical reports issued by the consortia and standardization working groups [7, 8]. As there are ongoing test site and testbed developments for specific application scenarios, our objective is to capture the latest understanding in the development of those applications.

In the future rigorous validation of specific systems can refine and tune these parameters.

The first eight applications in Table 3 enhance transportation safety; they are mostly ad hoc based, have relatively stringent time requirements, and are given high priority at the data link. Practically all of them rely on cooperative awareness beaconing at high beacon rates: 10 beacons/s or message period of 100 ms. Among them, *Pre-Crash Sensing* has the most stringent latency requirements. It is noteworthy that, for the time being, such latency figures are

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not tied to specific reliability levels. In fact, it is necessary to specify end-to-end delays (i.e., for V2V-enabled safety applications, maximum V2V application layer delays). This would include all processing at all layers and represent the delay after which the given event (vehicle detection, collision hazard, etc.) is perceived by the receiving vehicle. For multihop communication, the corresponding definitions would be necessary. It is also possible to adapt such requirements depending on the surrounding conditions.

From a different point of view, Pre-Crash Sensing is relevant to a small communication range (which corresponds to small distances between vehicles). Overall, the recommended ranges for each application can be beneficial to the protocol designer in many ways, for example, in terms of handling incoming messaging such as beacons.

Some of the transportation safety applications have relatively demanding positioning requirements: *Lane Change Warning* requires relative positioning accuracy of less than 2 m, whereas *Cooperative Forward Collision Warning* necessitates relative positioning accuracy of less than 1 m. The *Crash Avoidance Metrics Partnership (CAMP) Intersection Collision Avoidance* system, with two experimental intersections already deployed, requires relative positioning accuracy of less than 0.5 m. All vehicles and RSUs are to be location-aware, but GNSS-based or other localization schemes provide a coarser-grained level of accuracy than the above-mentioned requirements. As a result, additional onboard processing is necessary.

The next four applications (9–12 in Table 3) are related to transportation efficiency enabled by ad hoc communication with the infrastructure (RSUs, generic or specialized such as the toll collection units). The assigned priority is lower than that of safety applications, beaconing rates are five to ten times lower, and the required latencies are up to five times higher. The communication is based on V2V protocols too. But a distinctive feature, compared to safety applications that rely on broadcast, is that there is unicast V2V communication; in some cases, cellular communication could be involved.

The final four applications (13–16) offer services to users (passengers and drivers); they rely mostly on infrastructure-based communication rather than V2V data exchange and mandate Internet access. In other words, the vehicle has to be an IP addressable host, and the corresponding servers online and accessible either in an ad hoc V2I manner (when the vehicle is within range of an access point) or via cellular or other networks. Latency requirements are among the lowest, and cooperative awareness becomes secondary if not irrelevant. Nevertheless, other issues that are not VC-specific arise, such as digital rights management (i.e., mechanisms and policies that specify and enforce access control to the obtained content).

From the above discussion, we see a relation between communication and networking protocols and applications. Nonetheless, this is a joint development effort, and thus there are still aspects to be defined and fine-tuned. Several projects take for granted that there will be V2V

and V2I communication in the future, including the forms discussed in the previous sections. They consider an open VC architecture that makes data exchange possible, but they do not necessarily rely yet on advanced data exchange. This agnostic approach is interesting in the sense that one could develop an application without, or with little, VC now. In this vain, the Highly Automated Vehicles for Intelligent Transport (HAVE-IT) anticipates the availability of VC. The project is developing a co-pilot that optimizes task repartition between driver and co-driving system, with a redundant and fail-safe electronic architecture. The perception is currently local, but HAVE-IT prepares an architecture for cooperative data fusion in the future.

## FUTURE OUTLOOK

The surveyed recent concerted efforts have yielded significant results and momentum for further developments. In this article we provide a concise survey of the state of the art, capturing qualitatively and quantitatively the technical approaches under development.

Nonetheless, several challenges lie ahead before VC systems can be deployed. Continuing field tests, such as those undertaken by projects such as SAFESPOT and VSC-A, is paramount. Building large-scale field experimentation is further necessary for thorough testing and validation of the system dependability. This includes not only the data link and networking technologies but also the applications themselves, notably those with the most stringent requirements. Ensuring efficient and effective operation even in challenging situations, even if unlikely to occur in practice, is necessary (e.g., as the size of VC networks scales up).

Meanwhile, the integration of strong and efficient security mechanisms should not be neglected, especially as an architecture and protocols for secure VC along with privacy enhancing technologies are developed [9]. With the appropriate design, secure VC systems can be as effective as non-secure ones. Thus, with the current and growing awareness of the importance of security, trustworthy VC systems could be deployed.

Additional aspects to consider include financial, legal, and organizational issues. For example, what will be the cost of deployment, and how will it be covered? Will the deployment leverage on existing systems and user-portable devices, such as smart phones? What will be the first set of applications deployed? How will authorities and services be instantiated in a heterogeneous environment that is subject to legislation not necessarily or even far from harmonized?

Innovation is necessary, of course, in terms of market introduction. Without deep penetration of the solution (in vehicles and/or the infrastructure), benefits for the final user (the driver) will be very limited. No one would agree to pay for something that will be useful only at some time in the future. It is crucial to understand how VC can realistically be deployed. Responsibilities, legal implications, and liability issues should be clearly specified.

Another essential step toward deployment is standardization, with contributions from projects, industrial consortia, and standardization committees and working groups.

In the future, solutions departing significantly from the current paradigm could emerge. Advanced driver assistance systems and new sensing technologies can be highly beneficial, along with a large body of work on automated vehicles. Eventually, the most advanced cooperative systems would probably be fully automated; examples are the CyberCars and CityMobil projects and the DARPA Challenge (<http://www.darpa.mil>) for autonomous ground vehicles. Of course, very high levels of confidence would be necessary to gain broad user acceptance for vehicular communication systems, which could benefit personal and commercial mobility, contributing to their sustainability.

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