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A Method for Mapping V2X Communication Requirements to Highly Automated and Autonomous Vehicle Functions

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Abstract: The significance of V2X (Vehicle-to-Everything) technology in the context of highly automated and autonomous vehicles can hardly be overestimated. While V2X is not considered a standalone technology for achieving high automation, it is recognized as a safety-redundant component in automated driving systems. This article aims to systematically assess the requirements towards V2X input data to highly automated and autonomous systems that can individually, or in combination with other sensors, enable certain levels of autonomy. It addresses the assessment of V2X input data requirements for different levels of autonomy defined by SAE International, regulatory challenges, scalability issues in hybrid environments, and the potential impact of Internet of Things (IoT)-based information in non-automotive technical fields. A method is proposed for assessing the applicability of V2X at various levels of automation based on system complexity. The findings provide valuable insights for the development, deployment and regulation of V2X-enabled automated systems, ultimately contributing to enhanced road safety and efficient mobility.

Keywords: V2X technology; levels of autonomy; autonomous driving; sustainable traffic management

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1. Introduction

V2X (Vehicle-to-Everything) technology has long been discussed as a key element of autonomous mobility. It is anticipated that by end of the 2020s, all new commercial vehicles will be equipped with the technology to aid automated driving and assistance functions, improving mobility, safety and comfort [1,2]. The importance of this domain has been demonstrated in numerous technical reviews [3–6]. This trend has only been accelerated by the global demand during the COVID-19 pandemic [7], and further fuelled by the need for sustainable and ethical technologies [8,9].

Nevertheless, few articles dealt with the regulatory and standards aspects. It is believed that 5G, 6G and such technologies will empower most notably the new, autonomous system development in the domain of self-driving systems and telesurgery robots [10]. On the contrary to the common belief that V2X technology itself would enable vehicles for highly automated operation, the automotive community considers this technology as a safety-redundant component of automated driving systems [11]. Considering the ability of the vehicles to communicate with the environment as an extra set of sensors, all automotive development processes and the respective domains of operation are subject to the capabilities and limitations of V2X technology, as well as its integration with other sensors and components of the automated driving systems.

The safety integrity of automotive systems, including automated driving functions, is uniformly assessed by the ISO 26262 standard, defining their Automotive Safety Integrity Levels (ASIL) [12]. Based on the hazard analysis on severity, exposure and controllability, each component is assessed regarding to its contribution to the whole system. Highly automated systems require high ASIL integrity, where the information from V2X communication may be crucial to ensure coherence and redundancy in the system to increase road safety. Vehicles that are produced as of 2024 are not relying on V2X communication alone to contribute to driving functions, as this information is rather used to warn drivers or optimize global route planning. However, with the correct assessment of V2X technology capabilities mapped to the widely accepted Level of Autonomy (LoA), this type of sensory information may become integral part of environmental modeling, decision making and actuation in automated driving systems [13].

This article aims to systematically assess the requirements towards V2X input data to highly automated and autonomous systems that can individually or in combination with other sensors enable certain LoAs, defined by the Society of Automotive Engineers (SAE) International. The authors discuss regulatory challenges and the issue of scalability in the hybrid environments, where both V2X-capable and traditional vehicles are present on the roads, and map the V2X capabilities to the SAE levels of autonomy by taking into account the features that various protocols provide. A method is proposed for assessing the applicability of V2X at various levels of automation based on system complexity, and an example of the use of the method is provided on one of the common high level automation use-cases. This article is concluded with an outlook to non-automotive technical fields, where V2X-equivalent, IoT-based information is available, and may affect the operation of the automated systems.

2. State-of-the-Art V2X Technology

V2X, as a method for connecting vehicles to the environment first appeared in the late 1980s, and its primary aim was to reduce road accidents and increase traffic safety by information sharing between vehicles and autonomous systems. While the concept has been investigated by automakers and automotive suppliers, with the lack of standardized communication protocol and dedicated bandwidth, the information to be shared and the possible use cases were subjects to debate up until the early 2000s [14]. The first global standard for WLAN-based V2X communication was published by the Institute of Electrical and Electronics Engineers (IEEE) in 2010 [15]. The IEEE 802.11p standard supports a direct Vehicle-to-Vehicle (V2V) communication, as well as its extension to the infrastructure Vehicle-to-Infrastructure (V2I). Appointing a dedicated bandwidth, this standard aimed to provide a direct radio communication between the vehicles and their surroundings, theoretically enabling basic automated driving safety and comfort features, such as blind spot warning, forward collision warning and mitigation and platooning.

Since 2010, alternative protocols have been proposed based on cellular networks, which may extend or shift the operation domain of V2X aided autonomous systems. The advantages and disadvantages of using any of these protocols have launched a joint industrial and academic debate since the late 2010s [16]. The two most common V2X communication protocols are Dedicated Short-Range Communication (DSRC) and Cellular Vehicle-to-Everything (C-V2X). However, the underlying technology does not affect the assessment of the contribution of V2X technology to the levels of autonomy. While the discussion of industrial feasibility of these protocols does not form the scope of this paper, a general introduction of the scope of application and use cases are provided in this introductory section.

In recent years, V2X communication and development have faced several challenges. This paper does not aim to address the challenges of the underlying technology, rather it aims to focus on the implementation of new methodologies on automated driving use cases. However, some of these challenges are mentioned hereafter, serving as basis for further work and possible future development areas:

- Interference and Signal Degradation: In urban environments with high-density traffic, buildings and other obstacles, the radio signals can suffer interference or degradation, leading to signal loss or reduced quality of communication [17].

- Dynamic Network Topology: The network topology in V2X communication is highly dynamic due to the mobility of vehicles and changing environmental conditions. Maintaining reliable communication paths becomes challenging as vehicles move in and out of range or obstruct each other's signals [18].
- Latency and Delay: The time-sensitive nature of V2X applications, such as collision avoidance systems, requires low latency communication. However, delays in signal transmission or processing can occur due to network congestion, protocol overhead, or computational limitations in onboard systems, compromising reliability [19].
- Scalability: As the number of connected vehicles increases, the scalability of communication systems becomes crucial. Ensuring reliable communication among a large number of vehicles while maintaining network efficiency and avoiding congestion is a significant challenge [20].
- Security and Privacy: V2X communication involves the exchange of sensitive information related to vehicle location, speed and trajectory. Ensuring the security and privacy of these data against malicious attacks, such as spoofing, jamming, or eavesdropping, is essential for maintaining communication reliability and trust among the users [21].
- Harsh Environmental Conditions: V2X communication must operate reliably under various environmental conditions, including adverse weather (e.g., heavy rain, snow), electromagnetic interference and physical obstructions. Adapting communication protocols and signal processing techniques to mitigate the impact of these conditions is necessary for maintaining reliability [22].
- Quality of Service (QoS) Requirements: Different V2X applications may have varying QoS requirements in terms of reliability, latency and bandwidth. Ensuring that the communication system can meet these diverse requirements while optimizing resource utilization and network performance is a complex challenge [23].

2.1. Protocols of V2X Communication

2.1.1. DSRC Protocol

DSRC is a wireless communication protocol specifically developed for V2X communication. It operates at the 5.9 GHz frequency band and allows vehicles to exchange information within a range of up to 300–1000 m. DSRC supports direct V2V, V2I and V2P communication. It facilitates the exchange of safety-related information, such as vehicle position, speed, acceleration and basic safety messages. DSRC has been widely deployed and tested in various research projects and pilot programs around the world [24].

DSRC supports multiple communication modes to enable various types of V2X interactions, including:

- Vehicle-to-Vehicle (V2V): communication between vehicles. It allows nearby vehicles to exchange safety-critical information, such as speed, location, acceleration and braking status, enabling cooperative maneuvers and collision avoidance.
- Vehicle-to-Infrastructure (V2I): communication between vehicles and infrastructure components like traffic signals, roadside units, and toll booths. It enables the exchange of traffic-related data, such as signal phase and timing information, traffic conditions, and road hazards. V2I communication enhances traffic efficiency and supports applications like signal prioritization for emergency vehicles.
- Vehicle-to-Pedestrian (V2P): communication between vehicles and pedestrians carrying DSRC-enabled devices. This communication mode enhances pedestrian safety by providing alerts to both the driver and the pedestrian in potentially hazardous situations.

Other, less common uses of V2X include, but not limited to:

- Vehicle-to-Network (V2N): Involves communication between vehicles and the broader communication network, enabling access to cloud-based services, traffic information, and other centralized data sources.

- Vehicle-to-Grid (V2G): Allows electric vehicles to communicate with the power grid, enabling bidirectional flow of energy. This can be utilized for vehicle charging, discharging excess energy back to the grid, and participating in demand response programs.
- Vehicle-to-Cloud (V2C): Involves communication between vehicles and cloud-based platforms, enabling access to a wide range of services, including over-the-air updates, infotainment and personalized settings.
- Vehicle-to-Home (V2H): Enables communication between vehicles and smart home systems, allowing the integration of electric vehicles with home energy management for charging optimization and energy sharing.
- Vehicle-to-Device (V2D): Involves communication between vehicles and other connected devices, such as smartphones or wearables, to enhance the overall connected experience and provide additional services.

DSRC utilizes a standardized set of message formats to exchange information between vehicles and infrastructure. These messages follow the IEEE 802.11p standard, which is an amendment to the WiFi standard tailored specifically for vehicular communication [25]. Security is also a critical aspect of DSRC communication to prevent unauthorized access and ensure the integrity of the exchanged messages. DSRC incorporates security measures, including authentication, encryption and message integrity verification, to protect the confidentiality and authenticity of communication. DSRC has been standardized by organizations such as the IEEE and the SAE. Standardization ensures interoperability between different DSRC-enabled devices from various manufacturers, allowing seamless communication and compatibility across different V2X deployments.

DSRC has been extensively researched, tested and deployed in pilot programs and field trials worldwide. It has shown promising results in improving road safety, traffic efficiency, and enabling advanced V2X applications.

2.1.2. C-V2X Protocol

C-V2X is an evolution of V2X communication that leverages cellular network infrastructure for vehicle communication. It is based on the 4G LTE (Long-Term Evolution) and 5G cellular networks, allowing vehicles to communicate with each other, the infrastructure and the other road users. C-V2X offers several advantages, including enhanced coverage, extended communication range and the ability to leverage existing cellular network infrastructure. It supports both direct short-range communication (similar to DSRC) and network-based communication, enabling vehicles to access cloud-based services, such as real-time traffic information and remote vehicle diagnostics. C-V2X is gaining momentum and is expected to coexist and complement DSRC in future V2X deployments [26].

C-V2X utilizes the cellular network infrastructure to enable V2X communication. It operates in two modes: Direct Communication Mode (also known as PC5) and Network Communication Mode:

- Direct Communication Mode (PC5): In this mode, vehicles directly communicate with each other and nearby infrastructure using a PC5 interface. PC5 stands for "sidelink" and refers to the direct short-range communication between vehicles and infrastructure components without relying on the cellular network. It operates in the 5.9 GHz frequency band, similar to DSRC, and provides low-latency and high-reliability communication. PC5 allows vehicles to exchange safety-critical messages and information such as location, speed, acceleration and other relevant data. It enables direct V2V, V2I and V2P communications [27].
- Network Communication Mode: In this mode, C-V2X utilizes the cellular network infrastructure to enable wide-area communication and access cloud-based services. Vehicles can connect to the network through the cellular base stations and exchange information with other vehicles, infrastructure and centralized servers. Network communication mode allows for more extensive coverage and provides access to additional services, such as real-time traffic information, over-the-air software up-

dates, and remote diagnostics. It enables vehicle-to-network and vehicle-to-cloud communications, expanding the capabilities of V2X applications [28].

It is worth noting that the choice between DSRC and C-V2X as the preferred V2X communication protocol can vary depending on factors such as regional regulations, infrastructure availability, and industry standards, as shown in Figure 1. Different regions may prioritize different protocols and some deployments may even support both protocols simultaneously to ensure compatibility and interoperability between different vehicles and infrastructure systems. Challenges and potential solutions for enabling harmonious integration between DSRC and C-V2X have also been extensively studied, addressing the importance of coexistence mechanisms, to ensure interoperability and efficient utilization of the radio spectrum for V2X communication [29].

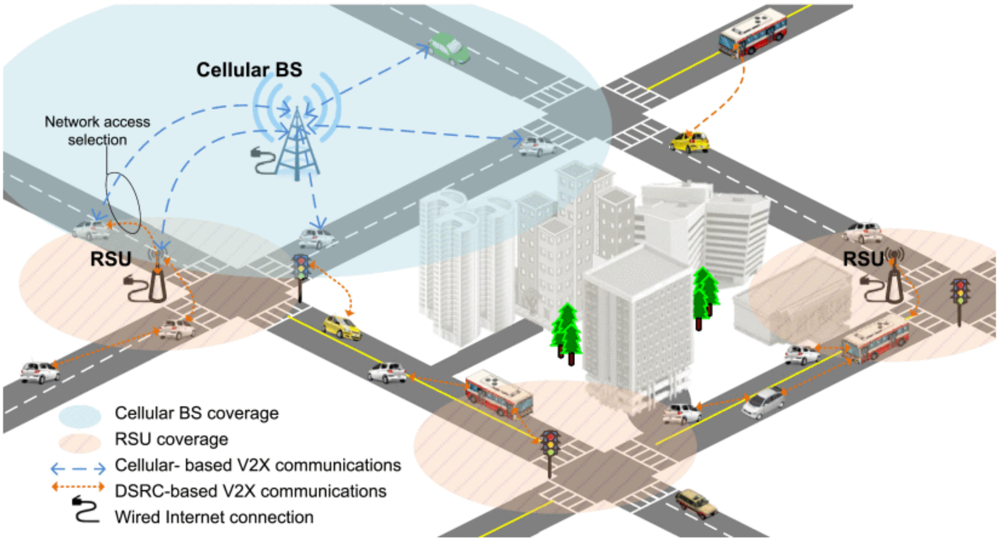

Figure 1. V2X communications in a DSRC–cellular hybrid urban scenario [29].

3. Related Work

Previous research efforts have extensively explored the integration of V2X technology with autonomous vehicles. Communication protocols such as DSRC and C-V2X have been investigated, along with various system architectures, including centralized and decentralized approaches. Researchers have explored applications of V2X technology in cooperative perception, platooning and intersection management [30]. Studies have focused on enhancing situational awareness, cooperative maneuvers and road safety through robust and reliable V2X communication. However, challenges such as communication reliability, security, scalability, and interoperability have been identified as key research areas for the successful deployment and adoption of V2X technology in autonomous vehicles [31].

A critical analysis of the intersection of the Internet of Vehicles (IoV) and sustainability is provided in [32]. The main contribution of the paper lies in the examination of the relationship between the IoV and sustainability, specifically focusing on the Environmental, Social and Corporate Governance (ESG) aspects. The paper highlights how IoV can positively impact environmental sustainability by improving traffic management, reducing emissions and enhancing fuel efficiency. It also discusses the social benefits, such as improved safety and increased accessibility, along with corporate governance considerations, including issues related to data privacy and security. By exploring these dimensions, it offers valuable insights into the potential advantages and challenges associated with the integration of IoV, offering a comprehensive perspective that can guide a responsible and sustainable implementation of the connected vehicle technologies.

One of the most comprehensive overviews of DSRC standards in the USA was published in 2015 by Stewart et al. [33]. The authors discussed the technical aspects, the regulatory framework and the deployment challenges of DSRC-based V2X communication.

Today, this work serves as a foundational reference for understanding DSRC technology and its applications in the context of intelligent transportation systems. With the emerging potential in cellular systems, Alsenwi et al. explored the potential of Cellular-V2X communication for future autonomous vehicles [34]. The work discussed the technical capabilities, performance and benefits of C-V2X compared to other V2X technologies, providing insights into the integration of C-V2X with cellular networks and its potential applications in autonomous driving scenarios. The importance of infrastructure communication through the Internet of Things for the integration of autonomous vehicles into traffic, highlighting various communication forms and potential challenges is discussed in [35]. The work suggests that investing in Vehicle-to-Infrastructure communication is crucial for ensuring safety, efficiency and energy conservation in autonomous vehicle traffic, proposing ideas and solutions to address these needs, including considerations for a new travel mode termed the Personal Transporter (PT). A more general overview was given by Filali et al. on connected vehicles, including system architectures, protocols, and applications. The paper discussed the challenges and solutions related to connectivity, security and interoperability in V2X communication, aided by a comprehensive review of the state-of-the-art in connected vehicles [36].

Existing work and use cases in the domain also address the key modern technologies in V2X communication such as cloudlets, attribute-based access control, industrial smart vehicles and authorization frameworks. A secure and trusted approach to V2V and V2I communication in ITS was proposed in [37], using edge infrastructures, introducing cloudlets for authorization, verification, and ensuring message integrity and anonymity, thus addressing concerns of location privacy and secure communication, with performance metrics discussed and compared to the existing ITS technologies. Formalized dynamic groups and Attribute-Based Access Control (ABAC) model (CV-ABAC-G) for smart cars ecosystem were introduced in [38,39], addressing security and privacy concerns by considering individual user preferences and introducing dynamic groups in vehicular IoT, with a proof of concept implementation in Amazon Web Services (AWS) cloud platform demonstrating real-world use cases and performance metrics. The related works above are based on a proposal for an authorization framework published in [40] from the University of Texas in San Antonio, aiming to enhance security and privacy in the Internet of Vehicles ecosystem, highlighting vulnerabilities in vehicular IoT and advocating for Extended Access Control Oriented (E-ACO) architecture to address dynamic interactions among entities, with a focus on vehicular clouds and various access control models, alongside discussing use cases and future research directions.

4. SAE Levels of Autonomy and V2X

SAE Levels of Autonomous Vehicles

Advanced driver assistant systems (ADAS) and automated driving systems are classified into various levels of autonomy based on their maturity and capability of handling complex driving scenarios with or without the contribution of the human driver. This classification is widely accepted by regulatory bodies and industry representatives, however, definitions are only addressing the functionalities of the final products, but do not address the capability requirements of the individual components building up the systems. The definition of the levels of autonomy was first introduced by the National Highway Traffic Safety Administration (NHSTA) in 2013 [41]. The proposal was later revised and completed by the Society of Automotive Engineers in the scope of the J3016_201609 taxonomy. The L0–L5 levels of autonomy have since became a standard for assessing the levels of automated systems within and beyond automotive applications [42]. This taxonomy has also been applied in the literature for fields closely related to automated driving, such as urban air mobility [43] and automated surgical procedures [44,45].

- *LoA 0: No driving automation*
  The vehicle does not possess the capability to carry out any automated actions. However, it can still transmit warning signals to the human operator. This limitation

underscores the crucial role of human oversight and decision-making in the operation of the vehicle. Despite advancements in automation and vehicle intelligence, the presence of a human operator remains essential to ensure safety and manage complex situations that may arise. By receiving warning signals, the human operator can stay informed about potential hazards or critical events, allowing them to intervene and take appropriate actions as necessary. The integration of warning systems with human–machine interfaces becomes crucial to effectively communicate critical information and enable timely responses for the human operator. Thus, while the vehicle lacks autonomous actuation abilities in these use-cases, it emphasizes the continuous importance of human involvement and situational awareness in ensuring safe and reliable vehicle operation.

- *LoA 1: Driver assistance*
  ADAS functionalities are enabled, primarily through automated control of either longitudinal (acceleration and deceleration) or lateral (steering) motions. However, it is important to note that the human operator is responsible for the overall control and operation of the vehicle. While the automated system assists in specific aspects of the driving task, such as maintaining a set speed or keeping the vehicle within its lane, the human operator retains the ultimate responsibility for monitoring the driving environment and making critical decisions.
- *LoA 2: Partial driving automation*
  The vehicle is empowered with the ability to be fully actuated by an autonomous system, enabling coordinated longitudinal and lateral control. The human operator remains actively engaged and responsible for overseeing the driving task. Their continuous involvement is essential to ensure a prompt and seamless transition of control when necessary. Nevertheless, the human operator's active engagement is pivotal. They must be ready to intervene and resume control of the vehicle immediately if the autonomous system encounters limitations or fails to handle certain driving situations. Effective monitoring of the driving environment, awareness of system capabilities and limitations, and the ability to respond promptly to unexpected scenarios are crucial aspects of the human operator's role in Level 2 automation.
- *LoA 3: Conditional automation*
  The dynamic driving task is primarily managed by the automated system. The human operator is actively supervising the system's operation. The automated system possesses advanced capabilities for environment recognition, decision-making, and control, enabling it to handle the entire driving task under specific conditions. One of the critical challenges in LoA 3 automation is the handover of control between the automated system and the human operator. It ensures that the human operator is always sufficiently aware and engaged to take over control is crucial to avoid potential hazards or delays in critical situations. Human–machine interfaces, clear communication, and proper training are paramount to facilitate effective control transitions and maintain the overall safety of the driving experience.
- *LoA 4: High automation*
  It represents a significant advancement in autonomous driving. At this level, the dynamic driving task is jointly performed by the vehicle's automated system, encompassing control, decision making, and environment recognition tasks. This joint performance is limited to a specific Operational Design Domain (ODD) defined by certain boundaries and conditions. In the event of a system malfunction or encountering tasks that exceed the system's capabilities, the vehicle is equipped with mechanisms to transit to a safe state. This ensures that the vehicle can mitigate risks and respond appropriately in challenging or unpredictable situations.
- *LoA 5: Full automation*
  It signifies the highest level of autonomous driving capability, where the automated system autonomously manages all dynamic driving tasks across any operational design domain without the need for human intervention. At this level, the vehicle is fully

self-driving, equipped with robust decision-making capabilities. It can navigate and adapt to a wide range of driving scenarios, including complex urban environments, highways, and challenging weather conditions.

5. V2X Technology in the Context of SAE Levels of Autonomy

The integration of V2X technology holds significant promise in advancing the capabilities of self-driving vehicles across the SAE levels. At levels where the human operator remains responsible, V2X can enhance driver assistance systems by providing real-time information about the road conditions, the traffic congestion, and the potential hazards, enabling the automated system to make more informed decisions. Complex ADAS systems can benefit from V2X in cooperative perception, allowing vehicles to exchange sensor data and collaborate in detecting and tracking objects. This can enhance the accuracy and the reliability of object recognition and improve the overall situational awareness of the automated system.

On the other hand, at higher levels of autonomy, V2X plays vital role in facilitating safe and efficient control transitions between the automated system and the human driver. Through communication with traffic infrastructure and other vehicles, V2X provides critical information to prepare the system and the driver for the handover of control. V2X is designed to enable highly cooperative and coordinated behaviors among self-driving vehicles. By sharing intentions, trajectories, and sensor data, V2X allows smooth merging, platooning, and intersection crossing, leading to improved traffic flow, reduced congestion, and enhanced safety.

5.1. Mapping of V2X Capabilities to the SAE Levels of Autonomy

In this paper, we propose a mapping of V2X capabilities to the SAE levels of autonomy by utilizing the features provided by communication protocols, integrated into automation levels.

- LoA 0—No automation. At Level 0, V2X technology refers to the communication and exchange of information between vehicles and the surrounding infrastructure, including other vehicles, pedestrians, traffic signals and road infrastructure. It enables vehicles to share real-time data such as speed, position and intentions with other connected entities, allowing for enhanced situational awareness [46]. At this level, V2X technology plays a crucial role in providing important safety-related information to the human driver, e.g., warnings about hazardous road conditions, traffic congestion or the presence of emergency vehicles. By transmitting this information, both situational awareness and decision making capabilities are significantly improved.
- LoA 1—Driver assistance. The human driver remains engaged and responsible for the driving task, V2X can augment the existing driver assistance features by enabling real-time communication between the vehicles, the infrastructure, and the other entities. In practice, this includes data on the speed and trajectory of nearby vehicles, enabling the automated system to maintain a safe distance and adapt the speed accordingly. At this level, V2X can support cooperative maneuvers and interactions between vehicles, such as cooperative merging or platooning. By exchanging information about trajectory or acceleration, the system can aid the human drivers to coordinate their movements more efficiently and smoothly.
- LoA 2—Partial driving automation. V2X communication enables cooperative perception and motion control between the vehicles and the surrounding environment. At this level, the automated system assumes control over both longitudinal and lateral motions, where V2X facilitates the exchange of sensor data between the vehicles. By sharing information about their own sensor readings, such as radar, LIDAR or camera data, vehicles can collectively improve their perception of the surrounding environment, enhancing the object detection, the tracking and the situational awareness, allowing the system to engage in more complex driving scenarios. LoA 2+ systems can also benefit from communicating the intentions of maneuvering functions, such

as lane changes, overtaking or merging, to nearby vehicles, enabling smoother and more coordinated movements. This cooperative behavior can enhance safety, reduce the risk of collisions and optimize traffic flow.

- LoA 3—Conditional automation. The automated system is responsible for controlling the vehicle and executing the driving task under certain conditions, while the human driver acts as a fallback and is required to intervene when prompted by the system. At this level, vehicle requires data from traffic infrastructure, such as the traffic lights or the road signs, and the other connected entities, including other vehicles and pedestrians, which are traditionally provided by the onboard sensor system. This information can assist the automated system in making informed decisions, adjusting its behavior and enhance the overall situational awareness of the automated system by providing advanced warnings and alerts. V2X communication can support the seamless transition of control between the automated system and the human driver. In case conditions exceed the capabilities of the automated system or require human intervention in the given ODD, V2X technology can facilitate the handover process.
- LoA 4—High automation. The automated system is capable of performing all dynamic driving tasks within a specific ODD without requiring human intervention. V2X technology contributes to this high automation level by facilitating the exchange of critical information between the vehicles and the infrastructure, enabling them to share real-time data about intentions, trajectories and sensor readings. This cooperative data sharing allows vehicles to have a comprehensive understanding of complex traffic scenarios. At this level, V2X technology contributes to safety and efficiency by enabling vehicles to communicate their ODDs and operational constraints. Through V2X, vehicles can broadcast their intended paths and driving behaviors to others, allowing for optimized route planning and avoidance of conflicts. This cooperative coordination can prevent potential collisions, enhance the traffic predictability, and improve the overall system performance. By integrating this information into their decision-making processes, autonomous vehicles can adapt their driving strategies accordingly and navigate safely within their designated ODDs.
- LoA 5—Full automation. V2X technology is expected to be an essential component in achieving Level 5 self-driving, where the vehicles are fully autonomous and capable of performing all dynamic driving tasks across all operational design domains without any human intervention. V2X enables seamless communication and coordination among the vehicles, the infrastructure and the other entities, therefore the autonomous systems are provided with comprehensive understanding of the surrounding environment and the behaviors of the other entities. By leveraging V2X capabilities, the autonomous vehicles can make highly informed decisions, optimize their routes, and navigate safely and efficiently in complex traffic scenarios. Through V2X communication, the vehicles can negotiate right-of-way, engage in cooperative merging and lane changes, and coordinate their speeds to maintain safe and efficient traffic flow. This cooperative interaction is crucial in creating a harmonious and predictable driving environment. V2X communication enhances the overall safety of Level 5 self-driving by providing advanced warnings and alerts. The vehicles can exchange information about potential hazards, road conditions, and unexpected events. This real-time information can be integrated into the decision-making processes of the autonomous vehicles, allowing them to proactively respond to changing situations and avoid potential collisions.

5.2. A Method for Assessing the Applicability of V2X at Various Levels of Automation

Assessing the applicability of V2X technology in different use cases of automated driving may prove challenging due to the complex interaction of the automated system and the environment. In order to employ a systematic approach in the planning phase of system design, this paper proposes a mapping of applicability of V2X technology in 6 major areas of interest, as shown in Table 1. The main investigated areas are:

- Smart infrastructure—the contribution to the dynamic driving task based on information from the static and dynamic environment;
- Driving strategy—long- and short term trajectory and path planning and navigation;
- Decision making—high-level driving logic behind the automated driving function;
- Collaborative driving—actuation commands and warning signals based on information sharing between the vehicles;
- Driver support—driver assistance in actuation and decision making, provided that control remains in the hands of the driver;
- Driver warning—information sharing about the environment and the status of the vehicle with the purpose of early warning.

Table 1 summarizes the main contribution of V2X technology to the dynamic driving task at various levels of automation. According to the applicability matrix, the nature of information transmitted by the communication network largely depends on the engagement of the human driver in the specific ODDs. At lower LoAs, V2X technology supports the driver with warning signals and increases traffic safety in ADAS functionalities, while at LoA 3–5 the emphasis of shared information is pivoting around collaborative and efficient traffic flow in line with the infrastructure and other traffic participants.

As it is shown in Section 6, the analysis of the dynamic driving tasks and mapping of components to the applicability matrix above, the design of the V2X system is possible at the function level, with special attention on the 6 main focus areas. This paper provides and example of this mapping to LoA 4 valet parking applications based on the method proposed, applying the SAE levels of autonomy context for V2X technology, provided in Section 5.1.

Table 1. Applicability of V2X at various levels of automation based on system complexity. At lower levels of automation, the contribution of V2X technology manifests in driver assistance and raising situational awareness. As the contribution of the human driver decreases at higher levels beyond driver assistance, the focus of information sharing between the vehicle and the environment shifts towards more complex automated functionalities. Table legend: ✓ Applicable ★ Optional ✗ Not applicable.

	Level 0 No Automation	Level 1 Driver assistance	Level 2 Partial driving automation	Level 3 Conditional automation	Level 4 High automation	Level 5 Full automation
Smart infrastructure	✗	✗	✗	✗	✓	✓
Driving strategy	✗	✗	✗	★	✓	✓
Decision making	✗	✗	★	✓	✓	✓
Collaborative driving	✗	★	✓	✓	✓	✓
Driver support	✗	✓	✓	✗	✗	✗
Driver warning	✓	✓	✓	✓	★	✗

5.3. V2X Aided Use Cases of Automated Driving

Through the implementation of wireless communication infrastructure, various applications leveraging V2X technology for autonomous vehicles have been explored, demonstrating notable attributes such as reliability, efficiency and security. State-of-the-art literature highlights numerous specific V2X-enabled cooperative autonomous driving scenarios, among which automated valet parking, intersection control and cooperative platooning are the most commonly cited use cases [47]. These scenarios encompass common urban road situations like valet parking and intersections, as well as cooperative platooning primarily considered on regular highways. Existing studies addressing different applications in this domain are typically categorized based on the target objects or locations, the maneuvers involved, and the associated algorithms employed.

Automated Valet Parking (AVP) is an advanced parking assistance system that leverages V2X communication to provide a driver-free parking service. AVP integrates real-time information, such as the availability of parking slots, the bookings by other vehicles, and the route plans, to assist drivers through wireless networks. The AVP system takes over the vehicle and manages the entire parking procedure, including the route planning, the execution and the parking. When the driver requests their vehicle, the system autonomously returns it to the transfer place. Due to the properties of AVP listed above, these systems are generally categorized into SAE Level 4 high automation solutions. Regarding serving targets, AVP systems cater to automated vehicles or a combination of regular and automated vehicles. Parking management, coordination of multiple vehicles, and addressing conflicts pose an entry point for V2X communication. Additionally, this allows the exploration of mixed traffic parking garages equipped with AVP, considering the parking requests from vehicles with varying automation levels [48].

Cooperative platooning is another example of LoA 3/4 automated driving use cases, where a group of vehicles travel together in a coordinated manner, with one vehicle acting as the leader and the others as members. Common driving operations within a platoon include acceleration, deceleration and lane-changing to maintain a stable and safe distance between the vehicles. Cooperative platooning aims to enhance traffic efficiency, capacity, driver convenience and to reduce fuel consumption. In practice, driving functions cover various operations to form, maintain and split platoons, control maneuvers within platoons and the algorithms employed for these maneuvers. Cooperative platooning is particularly beneficial when assisted by V2X equipment, as human-driven vehicles can show high uncertainty and randomness. Mixed platoons consisting of cooperative autonomous vehicles and human-driven vehicles have been explored, utilizing constrained Model Predictive Control (MPC) models to ensure smooth and stable traffic flow [49].

In LoA 3+ automated driving, controlled intersections play a crucial role in regulating vehicle movements, either through signal phases or basic traffic rules. Modern V2X-aided regulations aim to manage conflicts between vehicles entering from different directions. Fatal crashes, especially at uncontrolled intersections, account for a significant portion of overall traffic fatalities. While traditional approaches focus on signal logic design and intersection canalization to enhance efficiency, in the past years, Cooperative Intersection Control (CIC) has emerged as a promising method to improve safety, including signalized and non-signalized intersections, major CIC maneuvers, and the algorithms used for these maneuvers [50]. Virtual Traffic Lights (VTL) can replace traditional traffic lights by utilizing V2X communication. VTLs have been subject to recent studies, and experiments have shown successful coordination among vehicles [51]. Optimization algorithms, such as mixed-integer programming and advanced learning-based techniques like machine learning and reinforcement learning, are commonly used in CIC algorithms.

However, in current commercially available car models, V2X functionalities are limited to Level 0 warning signals to the driver. In 2019, the Car2X technology in the new Volkswagen Golf, for example, was rolled out to customers, which was marked as a major technological advancement within the V2X community, a concept shown in Figure 2 [52]. Car2X, a communication system enabling vehicle-to-vehicle and vehicle-to-infrastructure interactions in these models to facilitate real-time information exchange for improved road safety and enhanced traffic efficiency in these models. The Car2X system in the vehicle utilizes WLANp (Wireless Local Area Network for Public Transport) technology. This allows advanced warning capabilities that enable drivers to receive real-time information regarding accidents, roadworks, and emergency vehicles, empowering them to take appropriate actions well in advance. Car2X technology contributes to improved traffic flow and reduced congestion as well. The Volkswagen Golf equipped with Car2X can provide drivers with real-time data about traffic conditions and offer alternative routes, enabling them to avoid congested areas and optimize their travel time.

Figure 2. Volkswagen's integration of Car2X technology, utilizing the IEEE 802.11p WiFi standard, claims to enable secure and privacy-preserving communication between vehicles within an 800-m radius, marking an important milestone in local V2Vcommunication. *Image credit: DALL-E.*

Vulnerable Road User (VRU) protection has also gained attention lately. Autotalks, in collaboration with Volkswagen, Bosch eBike Systems and Commsignia, are set to showcase the capabilities of V2X communication in preventing bike-vehicle collisions. The demonstration, taking place at the SECUR Final Event near Paris, focuses on an obstructed intersection scenario where a car or eBike's vision is blocked. Using Autotalks' V2X technology integrated by Bosch eBike Systems and Commsignia software, a V2X-enabled bicycle will communicate with a VW vehicle to alert it on its presence, mitigating potential crashes at the intersection. This collaboration aims to enhance cyclists' safety and improve the integration of eBikes into future V2X communication. The SECUR project, an industrial consortium focused on V2X testing and assessment protocols for Euro NCAP, supports this initiative to leverage V2X technology for the safety of vulnerable road users, promoting cyclists' confidence and protection at intersections.

6. Case Study: Application of the Method on LoA 4 Valet Parking with V2X

In this section, we present a case study (automated valet parking) on the alignment the V2X capabilities with the SAE levels of autonomy, considering the features offered by various protocols. According to the proposed method, the investigated areas of interest can be mapped to the function to the extent of the function's level of automation according to SAE, carried our from the automated driving point of view. AVP is categorized as an LoA 4 function, as the ODD is limited to the parking lot or garage, however, the driver is not needed for the operation of the vehicle. AVP is also a special case of LoA 4 driving, as the physical presence of the driver in the vehicle is not required. The mapping of the function's requirements, components and challenges is done for the 6 areas of interest as follows.

6.1. Smart Infrastructure—AVP

Infrastructure in AVP covers both the parking lot or garage, where the maneuvering takes place and the section of the infrastructure that connects the parking area with the public road, where the function is activated. This includes any ramp, gate, parking bay or the section of the public road, where the LoA 4 function may be active.

For AVP, one of the most crucial V2X requirements is a the availability of local HD or feature maps, specific to the parking garage, provided in an appropriate format and available for storage on the vehicle. This is considered a *static* information and serves as a base for global trajectory planning. This information is completed with *dynamic* data from the infrastructure, which includes the list and location of free parking spots, any moving vehicle within the ODD and other information on the environment, such as temperature or humidity.

6.2. Driving Strategy—AVP

The driving strategy in AVP includes the global path planning from the entrance of the parking garage to the selected parking slot, the latter requiring V2X connection to the most up-to-date status of the available slots; the strategy also addresses the local path planning, which is defined in the vicinity of the final parking position, virtually blocking the path for other, simultaneously moving vehicles. Trajectory planning and execution requires precise localization from the vehicle, which can be done either by triangulation the position of the vehicle using locator sensor or using the AD sensor set for the execution of SLAM or other localization methods based on prior knowledge of the map of the infrastructure. Cloud-based computation is also possible for driving strategy, which requires the communication of the vehicle parameters and status to the central computing unit.

6.3. Decision Making—AVP

Decision making is one of the key elements of LoA 4–5 automated driving, which is particularly challenging in mixed—AD and non-AD—environments. In the case of fully automated AVP scenarios (no human driver are allowed), V2X serves as the interface for the swarm intelligence of active self-driving vehicles in the parking garage, transferring information back and forth between the actuators and a cloud-based computing unit to find the optimal planning and execution of the parking maneuver. This requires a low-latency, high bandwidth communication protocol to avoid delays and potential damage. In mixed environments, the decision making process is more complex, as the cloud-based system is not aware of the intention of human drivers, therefore more attention is given to the sensors mounted on the vehicles. In this case, the central computing unit relies on information transmitted from V2X-capable vehicles and static sensors mounted on the garage to estimate the intention and plan accordingly for human-operated vehicles.

6.4. Collaborative Driving—AVP

Collaborative driving in AVP is possible both by V2I and V2V communication, noting that the former approach may partially or fully fall into the area of decision making. However, collaboration is also possible on the V2V level by sharing sensor data and aiding local trajectory planning or evasion maneuvers, offloading the bandwidth load on the communication between the actors and the infrastructure. The information shared this way may include raw sensor data, (processed) information of the 3D environment, driving intentions, emergency status or other non-driving related information, such as outdoor conditions. Collaborative driving also helps the local solution of deadlock situations and facilitates the optimal use of parking slots in terms of fuel efficiency, time and other factors.

6.5. Driver Support—AVP

In LoA 4 AVP mode a vehicle is not providing driver support, as the system is capable (and required) to operate fully autonomously in the ODD, ideally without the presence of the human driver. In this case, driver support does not need to be implemented for AVP in the scope of V2X technologies.

6.6. Driver Warning—AVP

Driver warning may be chosen optionally for AVP in the scope of V2X, depending on the implementation of the functionality. In case LoA 4 AVP for any reason requires human presence in the vehicle during the maneuver, the system is required to inform and/or warn the driver on the current status of the parking maneuver through the infotainment system or other communication channels. This is not a critical element of the LoA 4 functionality, but may be a regulatory or safety requirement of the local government to be fulfilled. Driver warning may still be required if the human operator is not present in the vehicle. In these cases, the communication is done via notification messages, either about a successful/unsuccessful parking, or hazards in the garage or regarding the vehicle. This function requires the capability of the vehicle and the infrastructure to recognize these situations, assess their severity and send information to the human operator.

Using the summary presented in Table 2, one can plan the components and prepare the design definition of driving functions for an LoA 4 AVP system to address the requirements of this specific use case from the V2X technology point of view, following the steps outlined in Figure 3. Implementation requirements, test cases and test implementation are also integral parts of the automotive software development process, which has been defined and has been widely used in the industry, such as A-SPICE [53].

Table 2. Application of the proposed method of mapping ODD elements on automated driving functions for LoA 4 valet parking with V2X.

Smart Infrastructure	Driving Strategy	Decision Making	Collaborative Driving	Driver Support	Driver Warning
Static maps	Global path	Swarm intelligence	Shared data	N/A	Optimal status
Dynamic data	Local trajectory	Static sensors	-	N/A	Warnings

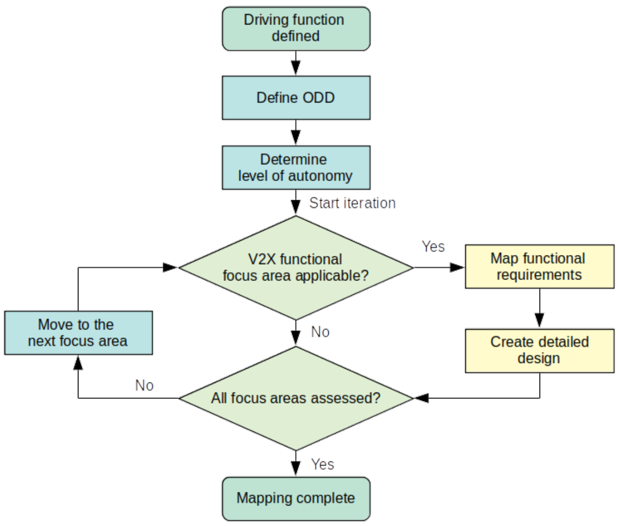

Figure 3. Steps and procedures of the proposed methodology visuzalized as a flow chart.

7. Sustainability of V2X Technology

V2X technology plays a significant role in promoting sustainability in the transportation sector. By enabling vehicles to communicate with each other and with surrounding infrastructure, V2X technology offers numerous benefits that contribute to a more sustainable and efficient transportation ecosystem [54].

One key aspect of V2X technology is its potential to improve traffic flow and reduce congestion. With real-time communication, the vehicles can share information about the traffic conditions, the road hazards and the optimal routes. This facilitates smoother traffic management and reduces unnecessary idling, resulting in lower fuel consumption, reduced greenhouse gas emissions and improved air quality. V2X technology also supports eco-driving practices by providing the drivers with information on the optimal acceleration, deceleration, and speed adjustments to maximize the fuel efficiency. By promoting eco-friendly driving behaviors, V2X contributes to reduced fuel consumption and lower carbon dioxide emissions.

V2X technology enables smart charging and grid integration for the Electric Vehicles (EVs) [55]. Through the Vehicle-to-Grid communication, EVs can interact with the electrical grid, allowing for optimized charging schedules based on the grid demand and the renewable energy availability. This bi-directional energy flow helps balance the grid, maximize the utilization of renewable energy sources, and reduce the reliance on conventional power generation.

8. Outlook to Related Fields

The emergence of V2X technology and the widespread availability of IoT-based information have the potential to revolutionize not only the automotive industry but also various non-automotive technical fields. Two prominent areas where these technologies can have a significant impact are the robotic surgery and the electric Vertical Takeoff and Landing (eVTOL) aircraft [43].

In the field of robotic surgery, V2X-equivalent, IoT-based information can enhance the capabilities of surgical robots and improve patient outcomes [56,57]. By leveraging real-time data from various sources, such as imaging devices, patient monitors and electronic health records, surgeons can access a comprehensive and up-to-date view of the patient's condition during the procedure. This information can enable more precise and informed decision-making, enhance surgical navigation, and improve the overall safety and efficiency of robotic surgeries both in local and long-distance (even transatlantic) use cases [14]. Studies in the field contribute to the understanding of communication protocols' performance and assist in selecting the most suitable protocol for resource-constrained robotic systems, such as minimally invasive surgical robotics [58].

Similarly, in the field of eVTOL aircraft development, V2X and IoT technologies can play crucial role in enabling safe and efficient operations [59]. These technologies can facilitate seamless communication between eVTOL vehicles, the air traffic management systems and the other stakeholders, ensuring coordinated and collision-free airspace usage. Real-time data exchange can enable dynamic route planning, weather monitoring and airspace congestion management, enhancing the safety and reliability of eVTOL transportation. Furthermore, V2X-equivalent, IoT-based information can support predictive maintenance and performance monitoring of eVTOL aircraft, optimizing their operational efficiency and reducing downtime.

While the integration of V2X and IoT technologies in these non-automotive fields holds great promise, several challenges need to be addressed. These include ensuring the security and privacy of sensitive medical data in robotic surgery, as well as establishing robust communication protocols and standards for eVTOL aircraft operations. By addressing these challenges and leveraging the potential of V2X-equivalent, IoT-based information, the fields of robotic surgery and eVTOL transportation can witness transformative advancements, leading to improved healthcare outcomes and revolutionizing the urban air mobility.

9. Discussion

V2X technology is expected to be equipped in all new vehicles by the end of the 2020s, supporting automated driving and safety features. However, it is not considered the sole technology enabling highly automated operation, but rather a safety-redundant component of the automated driving systems. V2X technology acts as an extra set of sensors, influencing the automotive development processes and operational domains. ISO 26262 standardizes the safety integrity of automotive systems, including automated driving, with different Automotive Safety Integrity Levels. While the vehicles produced since 2023 do not rely solely on V2X communication for driving functions, its assessment and integration into the system can enhance the environmental modeling, the decision-making and the actuation in automated driving. This paper explores the requirements, the regulatory challenges, the scalability and the potential impacts of V2X in highly automated and autonomous systems, along with its relevance in non-automotive fields with similar IoT-based information.

The integration of V2X technology in self-driving vehicles shows great potential for enhancing their capabilities across different levels of autonomy. At lower levels, V2X enables improved driver assistance systems by providing real-time information about the road conditions and the potential hazards. It also facilitates the cooperative perception, where vehicles exchange sensor data to enhance the object recognition and the situational awareness. At higher levels of autonomy, V2X plays a vital role in enabling safe control transitions between the automated systems the and human drivers. It allows the vehicles to communicate intentions, trajectories and sensor data, leading to coordinated behaviors such as merging and platooning, which enhance traffic flow and safety. V2X is crucial for achieving high levels of automation by facilitating critical information exchange between the vehicles and the infrastructure, optimizing the routes and avoiding collisions. Various use cases, including automated valet parking, cooperative platooning and intersection control, demonstrate the practical application of V2X technology in the autonomous driving.

10. Conclusions

The authors proposed a methodology to map the elements and focus areas of V2X technology in the scope of the automated driving, connecting the requirements to the functionalities of the highly automated driving system. The use case of the automated valet parking was presented as an application of the technology, where the mapping of the crucial aspects of the automated driving use case to the functionalities of the LoA 4 system were systematically reviewed, collected and summarized. The application of such methodology may provide an input for industrial design and production of the automated vehicles relying on V2X technology, adhering to the strict automated driving design and implementation standards of the automotive industry.

Literature research showed that while numerous works have discussed the current challenges and opportunities of the V2X technology itself, the domain of the applicability and methodical design of automated driving systems incorporating V2X technology has remained largely unexplored, indicating a significant gap in the existing body of literature. This study contributes novel insights into this relatively unaddressed area, providing special focus on the practical implementation and design considerations of automated driving systems leveraging V2X technology.

It was also shown that while sustainability, scalability, cyber-security and interoperability were arguably the key factors in the standalone development of V2X technology for the future of autonomy, automotive production standards and safety integration levels require a systematic process to system design, approaching key V2X fields from the point of view of the driving function realized on the vehicle, based on its level of autonomy.

Our future work includes the exploration of several important aspects to further advance the field of V2X communication. Possible directions include the development of standardized communication protocols and infrastructure requirements to ensure seamless interoperability among different V2X-enabled vehicles and infrastructure. Additionally, the integration of advanced machine learning and artificial intelligence techniques offers vast possibilities to enhance the performance and decision-making capabilities of V2X-enabled automated systems. The cyber-security challenges of the near future also require robust solutions to protect V2X communication from potential security threats, while exploring the social and legal implications of widespread V2X implementation, including ethical considerations, privacy concerns, and regulatory framework. All these directions provide a wide spectrum of research topics that can benefit from the foundations of this paper.

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Abbreviations

The following abbreviations are used in this manuscript:

ABAC	Attribute-Based Access Control
ADAS	Advanced Driver Assistance System
ASIL	Automotive Safety Integrity Level
AVP	Automated Valet Parking
CIC	Cooperative Intersection Control
DSRC	Dedicated Short-Range Communications
E-ACO	Extended Access Control Oriented
ESG	Environmental, Social and Corporate Governance
EV	Electric Vehicle
IEEE	Institute of Electrical and Electronics Engineers
IoT	Internet of Things
IoV	Internet of Vehicles
ITS	Intelligent Transport Systems
MPC	Model Predictive Control
NHSTA	National Highway Traffic Safety Administration
LoA	Level of Autonomy
PT	Personal Transporter
ODD	Operational Design Domain
SAE	Society of Automotive Engineers
V2C	Vehicle-to-Cloud
V2D	Vehicle-to-Device
V2G	Vehicle-to-Grid
V2H	Vehicle-to-Home
V2I	Vehicle-to-Infrastructure
V2N	Vehicle-to-Network
V2P	Vehicle-to-Pedestrian
V2V	Vehicle-to-Vehicle
V2X	Vehicle-to-Everything
VRU	Vulnerable Road User
VTL	Virtual Traffic Lights
VTOL	Vertical Take-off and Landing Vehicle

References

1. Porkolab, L.; Lakatos, I. Preparing of a Simulation System for an Examination of Non-Conventional Seating Positions in the Case of a Self-Driving Car. *Acta Polytech. Hung.* **2023**, *20*, 207–226. [CrossRef]
2. Takacs, A.; Drexler, D.A.; Galambos, P.; Rudas, I.J.; Haidegger, T.; Csizmadia, T. Automotive safety in the development pipeline of highly automated vehicles: Rethinking traditional automotive product-creation methods. *IEEE Syst. Man Cybern. Mag.* **2020**, *6*, 35–40. [CrossRef]

3. Han, J.; Shi, H.; Chen, L.; Li, H.; Wang, X. The car-following model and its applications in the V2X environment: A historical review. *Future Internet* **2021**, *14*, 14. [CrossRef]
4. Arena, F.; Pau, G. An overview of vehicular communications. *Future Internet* **2019**, *11*, 27. [CrossRef]
5. Bazzi, A.; Cecchini, G.; Menarini, M.; Masini, B.M.; Zanella, A. Survey and perspectives of vehicular Wi-Fi versus sidelink cellular-V2X in the 5G era. *Future Internet* **2019**, *11*, 122. [CrossRef]
6. Mohammed, D.; Horváth, B. Vehicle Automation Impact on Traffic Flow and Stability: A Review of Literature. *Acta Polytech. Hung.* **2023**, *20*, 129–148. [CrossRef]
7. Sayeed, A.; Verma, C.; Kumar, N.; Koul, N.; Illés, Z. Approaches and Challenges in Internet of Robotic Things. *Future Internet* **2022**, *14*, 265. [CrossRef]
8. Haidegger, T.; Mai, V.; Mörch, C.; Boesl, D.; Jacobs, A.; Rao R, B.; Khamis, A.; Lach, L.; Vanderborght, B. Robotics: Enabler and inhibitor of the Sustainable Development Goals. *Sustain. Prod. Consum.* **2023**, *43*, 422–434. [CrossRef]
9. Houghtaling, M.A.; Fiorini, S.R.; Fabiano, N.; Gonçalves, P.J.; Ulgen, O.; Haidegger, T.; Carbonera, J.L.; Olszewska, J.I.; Page, B.; Murahwi, Z.; et al. Standardizing an Ontology for Ethically Aligned Robotic and Autonomous Systems. *IEEE Trans. Syst. Man Cybern. Syst.* **2024**, *54*, 1791–1804. [CrossRef]
10. Haidegger, T.; Speidel, S.; Stoyanov, D.; Satava, R. Robot-Assisted Minimally Invasive Surgery—Surgical Robotics in the Data Age. *Proc. IEEE* **2022**, *110*, 835–846. [CrossRef]
11. Wang, J.; Shao, Y.; Ge, Y.; Yu, R. A survey of vehicle to everything (V2X) testing. *Sensors* **2019**, *19*, 334. [CrossRef]
12. *ISO26262*; Road Vehicles—Functional Safety. ISO: Geneva, Switzerland, 2011.
13. Abboud, K.; Omar, H.A.; Zhuang, W. Interworking of DSRC and cellular network technologies for V2X communications: A survey. *IEEE Trans. Veh. Technol.* **2016**, *65*, 9457–9470. [CrossRef]
14. MacHardy, Z.; Khan, A.; Obana, K.; Iwashina, S. V2X access technologies: Regulation, research, and remaining challenges. *IEEE Commun. Surv. Tutorials* **2018**, *20*, 1858–1877. [CrossRef]
15. *IEEE 802.11p*; IEEE Standard for Information Technology—Telecommunications and Information Exchange between Systems—Local and Metropolitan Area Networks—Specific Requirements—Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications—Amendment 6: Wireless Access in Vehicular Environments. IEEE: New York, NY, USA, 2010. [CrossRef]
16. Turley, A.; Moerman, K.; Filippi, A.; Martinez, V. C-ITS: Three observations on LTE-V2X and ETSI ITS-G5—A comparison. *NXP Semicond. White Pap.* **2018**, 1–6. Available online: https://www.nxp.com.cn/docs/en/white-paper/CITSCOMPWP.pdf (accessed on 1 March 2024).
17. Huang, J.; Fei, Z.; Wang, T.; Wang, X.; Liu, F.; Zhou, H.; Zhang, J.A.; Wei, G. V2X-communication assisted interference minimization for automotive radars. *China Commun.* **2019**, *16*, 100–111. [CrossRef]
18. Patra, D.; Chavhan, S.; Gupta, D.; Khanna, A.; Rodrigues, J.J. V2X communication based dynamic topology control in VANETs. In Proceedings of the Adjunct 2021 International Conference on Distributed Computing and Networking, Nara, Japan, 5–8 January 2021; pp. 62–68.
19. Lee, K.; Kim, J.; Park, Y.; Wang, H.; Hong, D. Latency of cellular-based V2X: Perspectives on TTI-proportional latency and TTI-independent latency. *IEEE Access* **2017**, *5*, 15800–15809. [CrossRef]
20. Shrestha, R.; Nam, S.Y.; Bajracharya, R.; Kim, S. Evolution of V2X communication and integration of blockchain for security enhancements. *Electronics* **2020**, *9*, 1338. [CrossRef]
21. Yoshizawa, T.; Singelée, D.; Muehlberg, J.T.; Delbruel, S.; Taherkordi, A.; Hughes, D.; Preneel, B. A survey of security and privacy issues in v2x communication systems. *ACM Comput. Surv.* **2023**, *55*, 1–36. [CrossRef]
22. Zhang, Y.; Carballo, A.; Yang, H.; Takeda, K. Perception and sensing for autonomous vehicles under adverse weather conditions: A survey. *ISPRS J. Photogramm. Remote Sens.* **2023**, *196*, 146–177. [CrossRef]
23. Torres-Figueroa, L.; Schepker, H.F.; Jiru, J. QoS evaluation and prediction for C-V2X communication in commercially-deployed LTE and mobile edge networks. In Proceedings of the 2020 IEEE 91st Vehicular Technology Conference (VTC2020-Spring), Antwerp, Belgium, 25–28 May 2020; pp. 1–7.
24. Kenney, J.B. Dedicated short-range communications (DSRC) standards in the United States. *Proc. IEEE* **2011**, *99*, 1162–1182. [CrossRef]
25. Eichler, S. Performance evaluation of the IEEE 802.11 p WAVE communication standard. In Proceedings of the 2007 IEEE 66th Vehicular Technology Conference, Baltimore, MD, USA, 30 September–3 October 2007; pp. 2199–2203.
26. Chen, S.; Hu, J.; Zhao, L.; Zhao, R.; Fang, J.; Shi, Y.; Xu, H. *Cellular Vehicle-to-Everything (C-V2X)*; Springer Nature: Berlin/Heidelberg, Germany, 2023.
27. Bazzi, A.; Berthet, A.O.; Campolo, C.; Masini, B.M.; Molinaro, A.; Zanella, A. On the design of sidelink for cellular V2X: A literature review and outlook for future. *IEEE Access* **2021**, *9*, 97953–97980. [CrossRef]
28. Ji, B.; Zhang, X.; Mumtaz, S.; Han, C.; Li, C.; Wen, H.; Wang, D. Survey on the internet of vehicles: Network architectures and applications. *IEEE Commun. Stand. Mag.* **2020**, *4*, 34–41. [CrossRef]
29. Amaran, M.H.; Noh, N.A.; Rohmad, M.S.; Hashim, H. Interworking of DSRC and Cellular Network Technologies for V2X Communications: A Survey. *Procedia Comput. Sci.* **2015**, *76*, 400–405. [CrossRef]
30. Xu, Y.; Zhou, H.; Chen, J.; Qian, B.; Zhuang, W.; Shen, S.X. V2X empowered non-signalized intersection management in the AI era: Opportunities and solutions. *IEEE Commun. Stand. Mag.* **2020**, *4*, 18–25. [CrossRef]

31. Vorobyev, A.; Pletnev, M.; Koveshnikov, A.; Vorobyeva, T.; Morozov, D.Y. Providing Additional Situational Awareness with the Use of V2X Technology to Improve the Reliability of Highly Automated Vehicles. In Proceedings of the 2021 Systems of Signals Generating and Processing in the Field of on Board Communications, Moscow, Russia, 16–18 March 2021; pp. 1–4.
32. Kostrzewski, M.; Marczewska, M.; Uden, L. The Internet of Vehicles and Sustainability—Reflections on Environmental, Social, and Corporate Governance. *Energies* **2023**, *16*, 3208. [CrossRef]
33. Stewart, R.R.; Protzel, S.O.; Tindall, P.A. Dedicated Short Range Communications (DSRC) Standards in the United States. *Proc. IEEE* **2015**, *103*, 1398–1410.
34. Alsenwi, M.S.; Al-Wahhab, H.Y. Cellular-V2X: C-V2X Communications for Future Autonomous Vehicles. *IEEE Commun. Mag.* **2018**, *56*, 128–134.
35. Zawodny, M.; Kruszyna, M. Proposals for Using the Advanced Tools of Communication between Autonomous Vehicles and Infrastructure in Selected Cases. *Energies* **2022**, *15*, 6579. [CrossRef]
36. Filali, F.; Maazouz, M.; Ghamri-Doudane, Y. Connected Vehicles: Solutions and Challenges. *IEEE Veh. Technol. Mag.* **2016**, *11*, 30–39.
37. Gupta, M.; Benson, J.; Patwa, F.; Sandhu, R. Secure V2V and V2I communication in intelligent transportation using cloudlets. *IEEE Trans. Serv. Comput.* **2020**, *15*, 1912–1925. [CrossRef]
38. Gupta, M.; Benson, J.; Patwa, F.; Sandhu, R. Dynamic groups and attribute-based access control for next-generation smart cars. In Proceedings of the Ninth ACM Conference on Data and Application Security and Privacy, Richardson, TX, USA, 25–27 March 2019; pp. 61–72.
39. Gupta, M.; Awaysheh, F.M.; Benson, J.; Alazab, M.; Patwa, F.; Sandhu, R. An attribute-based access control for cloud enabled industrial smart vehicles. *IEEE Trans. Ind. Inform.* **2020**, *17*, 4288–4297. [CrossRef]
40. Gupta, M.; Sandhu, R. Authorization framework for secure cloud assisted connected cars and vehicular internet of things. In Proceedings of the 23nd ACM on Symposium on access Control Models and Technologies, Indianapolis, IN, USA, 13–15 June 2018; pp. 193–204.
41. National Highway Traffic Safety Administration: Federal Automated Vehicles Policy. *Policy* **2013**, 13–14. Available online: https://www.nhtsa.gov/sites/nhtsa.gov/files/federal_automated_vehicles_policy.pdf (accessed on 1 March 2024)
42. Takács, Á.; Drexler, D.A.; Galambos, P.; Rudas, I.J.; Haidegger, T. Assessment and standardization of autonomous vehicles. In Proceedings of the 2018 IEEE 22nd International Conference on Intelligent Engineering Systems (INES), Las Palmas de Gran Canaria, Spain, 21–23 June 2018; pp. 185–192.
43. Takacs, A.; Haidegger, T. Infrastructural requirements and regulatory challenges of a sustainable urban air mobility ecosystem. *Buildings* **2022**, *12*, 747. [CrossRef]
44. Nagy, T.D.; Haidegger, T. Performance and Capability Assessment in Surgical Subtask Automation. *Sensors* **2022**, *22*, 2501. [CrossRef]
45. Pentek, M.; Zrubka, Z.; Gulacsi, L.; Haidegger, T.;Weszl, M.; Czere, J. 10 pragmatic points to consider when performing a systematic literature review of clinical evidence on digital medical devices. *Acta Polytech. Hung.* **2023**, *20*, 110–128.
46. Drexler, D.A.; Takács, A.; Nagy, T.D.; Haidegger, T. Handover Process of Autonomous Vehicles-technology and application challenges. *Acta Polytech. Hung.* **2019**, *16*, 235–255. [CrossRef]
47. Yang, X.; Shi, Y.; Xing, J.; Liu, Z. Autonomous driving under V2X environment: State-of-the-art survey and challenges. *Intell. Transp. Infrastruct.* **2022**, *1*, liac020. [CrossRef]
48. Schörner, P.; Conzelmann, M.; Fleck, T.; Zofka, M.; Zöllner, J.M. Park my car! automated valet parking with different vehicle automation levels by v2x connected smart infrastructure. In Proceedings of the 2021 IEEE International Intelligent Transportation Systems Conference (ITSC), Indianapolis, IN, USA, 19–22 September 2021; pp. 836–843.
49. Wang, P.; Di, B.; Zhang, H.; Bian, K.; Song, L. Platoon cooperation in cellular V2X networks for 5G and beyond. *IEEE Trans. Wirel. Commun.* **2019**, *18*, 3919–3932. [CrossRef]
50. Castiglione, L.M.; Falcone, P.; Petrillo, A.; Romano, S.P.; Santini, S. Cooperative intersection crossing over 5G. *IEEE/ACM Trans. Netw.* **2020**, *29*, 303–317. [CrossRef]
51. Zhang, R.; Schmutz, F.; Gerard, K.; Pomini, A.; Basseto, L.; Hassen, S.B.; Ishikawa, A.; Ozgunes, I.; Tonguz, O. Virtual traffic lights: System design and implementation. In Proceedings of the 2018 IEEE 88th Vehicular Technology Conference (Vtc-Fall), Chicago, IL, USA, 27–30 August 2018; pp. 1–5.
52. Farrag, S.G.; Outay, F.; Yasar, A.U.H.; Janssens, D.; Kochan, B.; Jabeur, N. Toward the improvement of traffic incident management systems using Car2X technologies. *Pers. Ubiquitous Comput.* **2021**, *25*, 163–176. [CrossRef]
53. Schäuffele, J.; Zurawka, T. *Automotive Software Engineering*; Springer: Berlin/Heidelberg, Germany, 2010.
54. Han, J.; Wang, X.; Shi, H.; Wang, B.; Wang, G.; Chen, L.; Wang, Q. Research on the Impacts of Vehicle Type on Car-Following Behavior, Fuel Consumption and Exhaust Emission in the V2X Environment. *Sustainability* **2022**, *14*, 15231. [CrossRef]
55. Elma, O.; Cali, U.; Kuzlu, M. An overview of bidirectional electric vehicles charging system as a Vehicle to Anything (V2X) under Cyber–Physical Power System (CPPS). *Energy Rep.* **2022**, *8*, 25–32. [CrossRef]
56. Amaran, M.H.; Noh, N.A.M.; Rohmad, M.S.; Hashim, H. A comparison of lightweight communication protocols in robotic applications. *Procedia Comput. Sci.* **2015**, *76*, 400–405. [CrossRef]
57. Fichtinger, G.; Troccaz, J.; Haidegger, T. Image-Guided Interventional Robotics: Lost in Translation? *Proc. IEEE* **2022**, *110*, 932–950. [CrossRef]

58. Patel, A.R.; Patel, R.S.; Singh, N.M.; Kazi, F.S. Vitality of robotics in healthcare industry: An Internet of Things (IoT) perspective. *Internet Things Big Data Technol. Next Gener. Healthc.* **2017**, 91–109. [CrossRef]
59. Bathla, G.; Bhadane, K.; Singh, R.K.; Kumar, R.; Aluvalu, R.; Krishnamurthi, R.; Kumar, A.; Thakur, R.; Basheer, S. Autonomous vehicles and intelligent automation: Applications, challenges, and opportunities. *Mob. Inf. Syst.* **2022**, *2022*, 7632892. [CrossRef]