electronics

MDPI

Article

Digital Infrastructure Quality Assessment System Methodology for Connected and Automated Vehicles

Boris Cucor [1], Tibor Petrov [2], Patrik Kamencay [1,*], Marcel Simeonov [1] and Milan Dado [1]

[1] Faculty of Electrical Engineering and Information Technology, University of Zilina, 010 26 Zilina, Slovakia; boris.cucor@feit.uniza.sk (B.C.); simeonov1@stud.uniza.sk (M.S.); milan.dado@uniza.sk (M.D.)

[2] Department of International Research Projects—ERAdiate+, University of Zilina, 010 26 Zilina, Slovakia; tibor.petrov@uniza.sk

* Correspondence: patrik.kamencay@feit.uniza.sk

Abstract: The rapid integration of Connected and Automated Vehicles (CAVs) into modern transportation systems necessitates a robust and systematic approach to assess the quality of the underlying digital infrastructure. In the presented work, we propose a methodology and evaluation of framework that can be used to assess digital infrastructure segments based on their readiness for the deployment of CAVs. The methodology encompasses a comprehensive framework that collects, processes, and evaluates diverse data sources, including real-time traffic, communication, and environmental data. The proposed framework is developed based on experimental data and provides a systematic approach to assess infrastructure readiness for CAVs. The proposed methodology is applied in a system for detecting the readiness status of digital infrastructure from a Cooperative, Connected, and Automated Mobility (CCAM) perspective. The system can determine the percentage of non-compliance of technical service requirements in terms of latency, bandwidth, and localization accuracy. Thanks to this, we can determine in advance in which state the current digital infrastructure is and which services can be currently operated, and thus locate the segments of the route in which the telecommunication systems need to be supported.

Keywords: connected and automated vehicles; 5G; CCAM services; 5G requirements; readiness assessment; vehicular communication; digital infrastructure; bandwidth; latency; localization

check for updates

Citation: Cucor, B.; Petrov, T.; Kamencay, P.; Simeonov, M.; Dado, M. Digital Infrastructure Quality Assessment System Methodology for Connected and Automated Vehicles. *Electronics* **2023**, *12*, 3886. https://doi.org/10.3390/electronics12183886

Academic Editor: Dongkyun Kim

Received: 10 August 2023
Revised: 8 September 2023
Accepted: 11 September 2023
Published: 14 September 2023

1. Introduction

Cooperative, Connected and Automated Mobility (CCAM) is expected to significantly contribute to increased road safety, inclusiveness of transport services, and the reduction of road transport emissions. In many regards, contemporary vehicles are already connected devices, taking advantage of information and entertainment services delivered to the driver thanks to internet connectivity [1]. With the ability to communicate, road users may even interact with each other and coordinate their actions, resulting in safer and more efficient operation through enhanced situational awareness. For more than a decade, this concept, known as Cooperative Intelligent Transport Systems (C-ITS) in Europe, has been thoroughly researched, tested, and enhanced. While conventional communication technologies may provide an acceptable level of reliability for infotainment services, many studies conducted in the early years of C-ITS research demonstrated that to support safety-related applications in road transport, dedicated technologies providing much lower end-to-end latency in highly dynamic environments might be necessary. This fact led to the development of communication systems based on Dedicated Short-Range Communications (DSRC). DSRC-based technologies for vehicular communications, standardized as IEEE WAVE in North America and ETSI ITS in Europe, provided low-latency ad hoc communication suitable for rapidly changing network topologies in vehicular environments. These technologies were considered a de facto industry standard for vehicular communications until the Cellular Vehicle-to-Everything (C-V2X) technology was introduced in 3GPP Release 14 in 2016.

On one hand, C-V2X technology promised to tackle the main limitations of DSRC-based vehicular communications such as relatively low data rate, poor scalability, and limited message delivery ratio in challenging communication conditions. On the other hand, C-V2X based on 4G cellular networks comes with its own set of limitations, as discovered by some studies, such as higher latency [2] and lower Packet Delivery Ratio (PDR) [3,4] in certain scenarios.

Sidelink interface PC5 was first introduced in 3GPP Release 12 to enable direct device-to-device communications in the context of cellular networks [5]. Release 12 defines two modes of sidelink operation: mode 1 where the network resources are allocated with the help of the cellular network, i.e., the communicating nodes must be within a base station coverage; and mode 2 where nodes assign network resources themselves autonomously, without the need to be within a base station coverage. Similarly, 3GPP Release 14, which introduced sidelink communications for vehicular networking specifically, defines two modes of sidelink communication:

- LTE PC5 mode 3, which supports direct broadcast communication between terminals, provides network resources to vehicles through the network, hence requiring connectivity between vehicles and the base station. Since the resources are allocated centrally, the cellular network may improve QoS and scalability and reduce interference between vehicles [6];
- LTE PC5 mode 4 also supports direct broadcast communication between terminals; however, vehicles assign themselves network resources autonomously using Sensing-based SemiPersistent Scheduling (S-SPS) algorithm [7]. While network coverage is not required, this mode is prone to packet collisions when the network load and channel congestion increase [8,9].

In 2020, 3GPP introduced Release 16 which brought two new PC5 modes based on 5G New Radio (NR) for vehicular communications [10]:

- NR PC5 mode 1, which supports direct broadcast, groupcast, and unicast communication between terminals, provides network resources to vehicles through the network, hence requiring connectivity between vehicles and the base station;
- NR PC5 mode 2 supports direct broadcast, groupcast and unicast communication between terminals. Vehicles assign themselves network resources autonomously and they are not required to be within base station coverage.

Additionally to sidelink communication, terminals can utilize the traditional cellular Uu interface to facilitate LTE-based C-V2X and 5G-based C-V2X communication through a base station in the cellular network. If utilized by vehicles, this mode of communication is often referred to as Vehicle-to-Network (V2N) communication [11,12]. Uu interface is also likely to be utilized for facilitating communication between users where a dedicated terminal would be impractical and/or not necessary. A good example may be pedestrians, who are not likely to carry a dedicated communication device to support transport telematics applications. Instead, many of them already use a smartphone equipped with many sensors and communication capability through LTE Uu or 5G Uu interfaces. These devices can be used to support applications based on Vehicle-to-Pedestrian (V2P) communication, such as [13–15].

Many traffic safety and efficiency services based on V2X communications taking advantage of this wide range of communication technologies have already been well defined and even tested under real traffic conditions. However, new services are expected to emerge, especially with the advent of automated vehicles which will require high bandwidth, extremely low latencies, and ultra-reliable communication.

With the ongoing deployment of commercial 5G networks, the bandwidth available to users should increase significantly. Many locations around the world, especially in cities, are already covered by 5G non-standalone (NSA), or even 5G standalone (SA) network coverage. The aim of this study is to consolidate the known communication requirements of V2N C-ITS applications and measure the readiness of contemporary 5G networks to support those requirements through a case study conducted in the city of Zilina, Slovakia. To measure the selected parameters of the communication network, we developed and present herein a methodology for data collection and processing which can be also applied in other locations worldwide. The results of this work may prove useful for cellular network service providers interested in identifying the readiness of their network on V2N C-ITS services in certain locations. Performing an assessment of the target location using the presented methodology can help them plan the development of their cellular infrastructure more efficiently by providing insight on most underserved areas and interventions needed to increase the readiness of the 5G network for V2N C-ITS services in the target area.

Our Contribution

Our work is divided into five sections. The state of the art is described in Section 1. In this section, we introduce readers to the issues of vehicular communication networks and next-generation networks. We also discuss the proposed framework of minimum technical requirements to support V2N C-ITS services. The framework is based on a review of scientific articles and technical documentation by a coalition for the development and promotion of standardised protocols for automotive vehicles using 5G communications. In Section 2, we discuss methodology, where we introduce readers to the proposed methodology for digital infrastructure research. We describe the investigated parameters of communication and localization and show the proposed procedure for processing the investigated parameters. In the next section, the data collection and processing are described (5G Network Parameters Evaluation). In Section 4, we describe the parameter estimation and obtained experimental results.

The overall contributions of this paper can be summarized as follows:

- We reviewed the literature defining communication and localization requirements of envisaged C-V2X services based on V2N communication. The reviewed literature consists of scientific publications, research project reports, and publications of organisations involved in V2X research and development. We compiled the communication and localization requirements of V2N C-ITS services in the form of an easy-to-follow table.
- We developed a methodology for data collection and processing in order to evaluate the readiness of commercial 5G networks to support V2N C-ITS services.
- We demonstrated the application of the developed methodology by evaluating the readiness of 5G network to support V2N C-ITS services in a case study conducted in the city of Zilina, Slovakia, identifying areas underserved by the currently deployed 5G infrastructure.

2. Materials and Methods

The development of the Digital Infrastructure Quality Assessment System (DIQAS) methodology for CAVs necessitates a comprehensive approach to data collection and preparation. Accurate and relevant data serve as the foundation for the assessment of digital infrastructure quality. To assess the quality of digital infrastructure for CAVs, a set of pertinent quality metrics were chosen. These metrics were derived from established transportation engineering principles and tailored to the context of digital infrastructure. The selected metrics included:

- Latency and Communication Reliability: Measuring the delay in data exchange between vehicles and infrastructure, along with the reliability of communication links.
- Position Accuracy: Evaluating the precision of location data provided to CAVs for navigation and decision-making.
- Traffic Data Integrity: Assessing the accuracy of real-time traffic information shared with vehicles to optimize routes and avoid congestion.

2.1. Vehicle-to-Network Services and Communication Requirements

In this subsection, we present the overview of Vehicle-to-Network (V2N) C-ITS services which are currently under development and their communication requirements. Based on analysis of the available literature including research papers, research project deliverables, and standardization documents [16–33], we compiled a communication and localization requirements framework of envisaged V2N C-ITS services. The example of the framework is illustrated in Table 1 and the full framework containing requirements for all investigated V2N C-ITS services is presented in Tables A1 and A2. The framework is divided into eight columns. The first column represents the parallel 3GPP version labeling system to which the provided service refers. In the second column is a list of all provided services. In the next four columns, we provide the minimum technical requirements for the services in terms of upload speed, download speed, latency, and localization accuracy. For a deeper specification, we describe in the seventh column the type and message generation frequency of the provided service. The services are divided into basic and advanced as is shown in Table 1. The basic services are those that are provided as a baseline in CCAM technologies. In contrast to advanced services, basic services are not technically challenging in terms of minimal requirements. As an example, we consider the Software Update service. According to [26], this service does not require any minimum requirements in terms of upload speed and latency. In terms of download speed, the service requires a minimum available speed of 30,000 kbit/s. A minimum accuracy of 30 m is required in terms of location accuracy. Localization is used in this service to determine the country in which the vehicle is located. Each state may have its own legislation and regulations governing the individual update modules. By identifying the state, we can determine which update module is used. As an example, we discuss the advanced service Software Update of Reconfigurable Radio System. This service is used for updating communication systems. Each country may have different specifics for reserving CV2X communication bands and therefore state identification is required. On the other hand, the advanced service accident report requires a fairly accurate positioning with a maximum deviation of 1.5 m, according to [29].

Table 1. Example of communication and localization requirements of selected Vehicle-to-Network (V2N) Cooperative Intelligent Transport Systems (C-ITS) services.

3GPP Rel.	Service	Uplink [Kbit/s]	Downlink [Kbit/s]	Latency [ms]	Position Accuracy [m]	Message Generation Frequency and Type	Service Level Reliability [%]
			Basic V2N C-ITS services				
8	Software Update [26]	-	300,000	N/A	30	-	N/A
			Advanced V2N C-ITS services				
14	SW Update of Re-configurable Radio System [26]	-	440	N/A	30	N/A	99%
16	Accident Report * [29]	1800	-	-	1.5	N/A - Sensor data prior to and after the collision	99.99%

* The service may have variations requiring higher 3GPP Release features.

Based on the developed framework, we conclude that the services provided by the C-V2X Uu interface do not present high technical requirements in terms of download and upload speed. On the other hand, the higher technical requirements focus specifically on communication latency and location accuracy. Some of the services require a minimum latency of 10 ms which represents a high technical challenge for current networks. This can be solved by integrating new-generation networks that use the terahertz frequency band with the support of satellite systems. The low latency requirements are induced by traffic safety considerations. Vehicles in these networks receive and send data that must be processed in time. These data are evaluated in order to make decisions and control the vehicle. From a location perspective, many services require a minimum accuracy of 0.1 m. In commercially available Global Navigation Satellite System (GNSS) location services, this accuracy cannot be achieved. This can be solved by integrating Real-Time Kinematic (RTK) technology and introducing new services for CCAM from a GNSS perspective. We note that in case of non-compliance with the specified technical requirements, the operation of CCAM technology could have serious consequences in terms of safety. In the further process of our research, we used this framework as a methodology for a comprehensive digital infrastructure readiness assessment system.

3. 5G Network Parameter Evaluation

The successful deployment of autonomous mobility heavily relies on robust and reliable communication networks, such as 5G, to enable real-time data exchange and decision-making. This study focuses on assessing the latency and throughput of the 5G network along a specific route in city of Zilina. For this purpose, we obtained the locations and distribution of 5G base stations across the city from the local network infrastructure provider. The objective is to gauge the readiness of the 5G network in supporting the communication requirements of autonomous vehicles.

3.1. Data Collection and Data Processing

To evaluate the latency and throughput of the 5G network, we conducted extensive measurements along the chosen routes in the city of Zilina, which included segments near points of interest, an industrial zone, and a suburban area. Using a smartphone with 5G support (measuring device), we collected data on latency, uplink speed, and downlink speed at various times of the day. In Figure 1, we can see a representation of the trajectories of the measured routes.

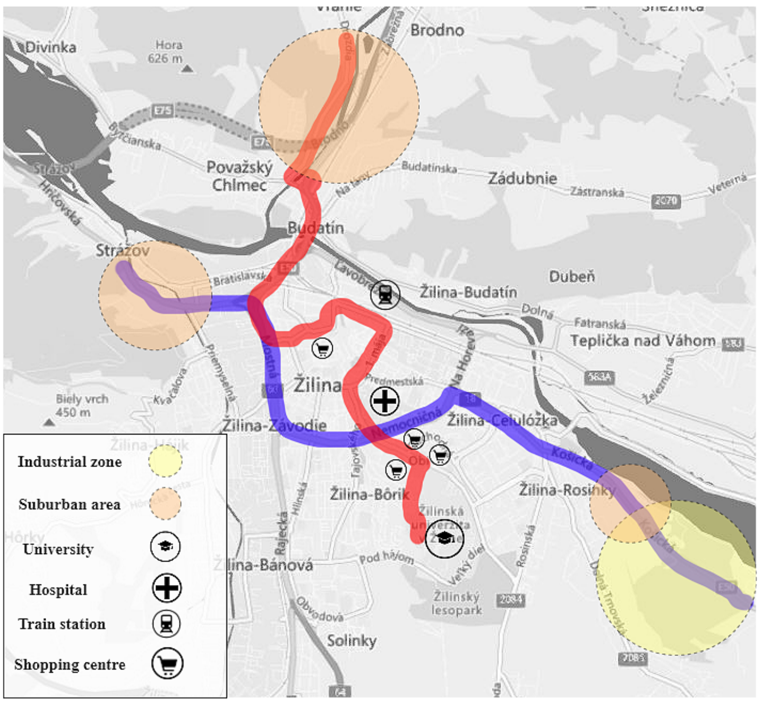


Figure 1. Investigated route 1 (red) and route 2 (blue).

Route 1 is shown in red color and route 2 is shown in blue color. We chose the routes based on several criteria, depending on the changing environment in which the vehicle is moving (speed, traffic density, building density, etc.). The trajectory of the routes covers partly urban and partly suburban areas. The development of the DIQAS methodology for CAVs necessitates a comprehensive approach to data collection and preparation. Accurate and relevant data serve as the foundation for the assessment of digital infrastructure quality. The following subsections outline the methodologies used for data preparation and processing.

3.2. Proposed Research Methodology for Communication and Localization Data

For latency analysis, we created a 300 B packet size, which we sent every 100 ms to a remote server. The 300 B packet size is set as a standard packet size for CCAM communication [34]. Each packet received by the server was timestamped by the Network Time Protocol (NTP) and sent back to the measurement device. This allowed us to measure packet loss also and calculate the latency of two-way communication (Δ_t). This was calculated as a function of the packet transmission time (t_{tx}) and the packet reception time (t_{rx}) as is shown in the following equation:

$$\Delta t[\text{ms}] = t_{rx} - t_{tx}. \quad (1)$$

The communication bandwidth was collected by a measurement device that continuously downloads a 2 GB file. The file was downloaded at 10 s intervals from a remote server that had a stable 600 MBit/s connection. The size of the file and download time were set to ensure that the file would never be downloaded, as we recorded the actual download speed (Downlink) during the download process. The uplink speed was recorded by the reverse process. The measuring device uploaded the file to the remote server at 10 s intervals and during this process, we recorded the actual uplink speed. In Figure 2, we can see the proposed process for the investigation of 5G communication and localization parameters.

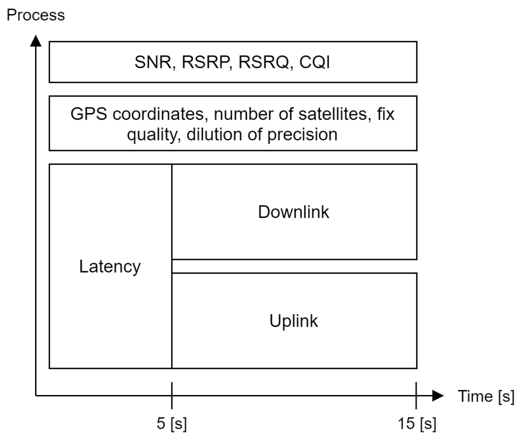


Figure 2. Proposed process for 5G communication and localization parameters research.

In the first phase of the research, we collected the two-way communication latency. The 5 s are allocated for this process. After performing this process, we collected the bandwidth. The time for the bandwidth parameter collection had to be large enough to record the bandwidth at the correct values. When this process is run, the bit rate increases linearly which takes some time to reach the maximum bit rate. For this reason, we set aside 10 s to investigate the bandwidth parameters of the network. During the two mentioned processes, telemetry of the location systems such as Global Positioning System (GPS) coordinates, the number of satellites, fix quality, dilution of precision and telemetry from 5G communication such as Signal-to-Noise Ratio (SNR), Reference Signal Receive Power (RSRP), Reference Signal Receive Quality (RSRQ), and Channel Quality Indicator (CQI) were continuously investigated.

Multiple measurements were performed at different times of the day to account for potential variations in network performance. Finally, we took a total of 10 measurements on each route. This study focuses on analyzing the latency and bandwidth of the 5G network in the context of autonomous vehicle use cases. The data processing procedure is divided into three main parts of (as is shown in Figure 3) data preprocessing, data sorting, and statistical evaluation. The measured data, initially stored as text files (.txt), are converted to a machine-readable format (Comma-Separated Values-csv) through a proposed process. The converted data are then used as input for the data sorting phase, where individual data are sorted and synchronized based on time stamps obtained using NTP and location stamps. Finally, statistical evaluation techniques are employed to quantify the quality of the digital infrastructure parameters.

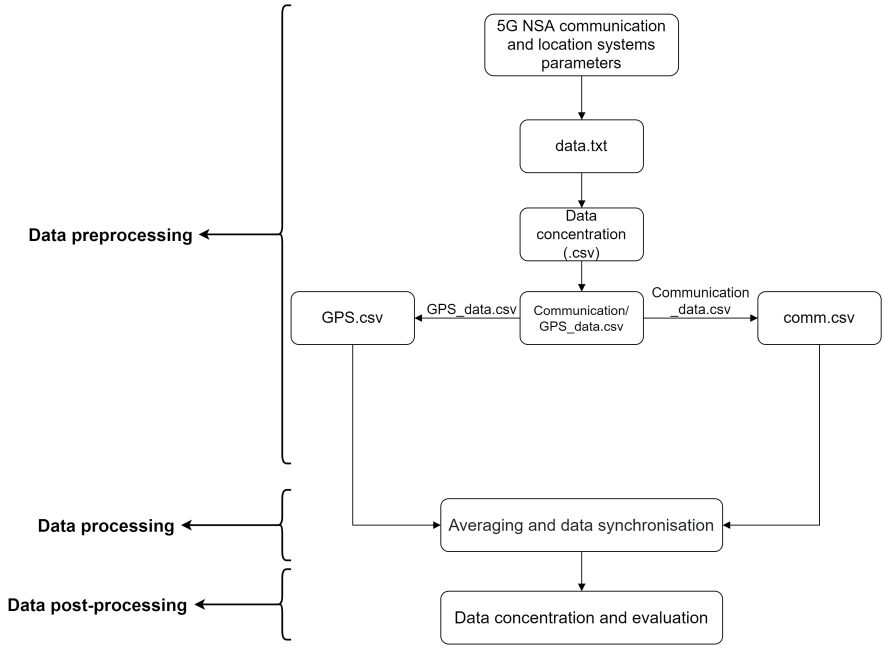


Figure 3. Proposed data processing of 5G communication and localization parameters.

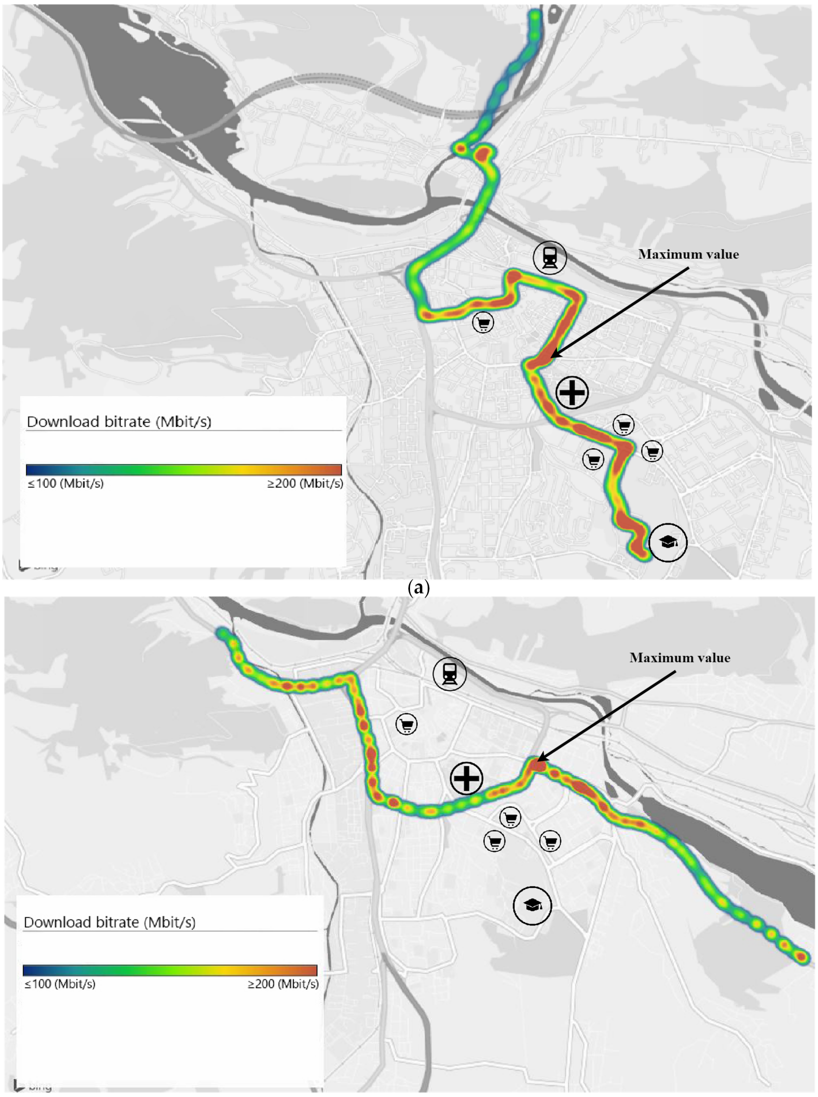
The results of this study provide valuable insights into the latency and bandwidth of the 5G network for autonomous vehicle use cases. By employing the proposed data processing procedure, we were able to convert the measured data from .txt to .csv format, enabling efficient further processing. The data sorting phase ensured that the individual data were accurately represented and synchronized based on time and location stamps. The statistical evaluation of the sorted and synchronized data allowed us to quantify the quality of the digital infrastructure parameters. This analysis provided valuable information on the performance of the 5G network, shedding light on its suitability for autonomous vehicle operations. The results obtained from this study can aid in optimizing the network infrastructure and improving the overall performance of autonomous vehicles.

4. Parameter Evaluation and Results Achieved

In this part, we focused on the evaluation of the collected parameters of the 5G NSA communication system, which are: downlink, uplink, latency, and, in the context of location-based systems, localization accuracy. Our analysis of the collected data revealed noteworthy findings regarding the latency and throughput of the 5G network in Zilina's designated areas. In the segments near points of interest, we observed higher latency levels, indicating potential challenges for real-time communication and decision-making in autonomous mobility scenarios. Similarly, the uplink and downlink speeds were lower in the suburban areas and the industrial zone, implying potential limitations in data exchange and transfer. The 5G network promises enhanced connectivity and faster data transfer speeds, making it particularly suitable for autonomous vehicles and other bandwidth-intensive applications. Understanding the variations in network parameters along different routes is crucial for optimizing network performance. This part of the study aims to analyze network parameters on route number 1 and route number 2 in the 5G network, using a heat map visualization technique. The collected data were used to generate a heat map, where different colors represent varying parameters. The heat map provides a visual representation of the variations in network parameters along the routes.

4.1. Downlink

In this part, we focus on analyzing the average downlink speed on route number 1 and route number 2 in the 5G NSA network. A heat map visualization technique is employed to represent the variations in downlink speed along these routes. In Figure 4, we can see a heat map that shows the average downlink speed on route number 1 and number 2.



(**b**)

Figure 4. Average downlink speed on the route (**a**) number 1 and (**b**) number 2.

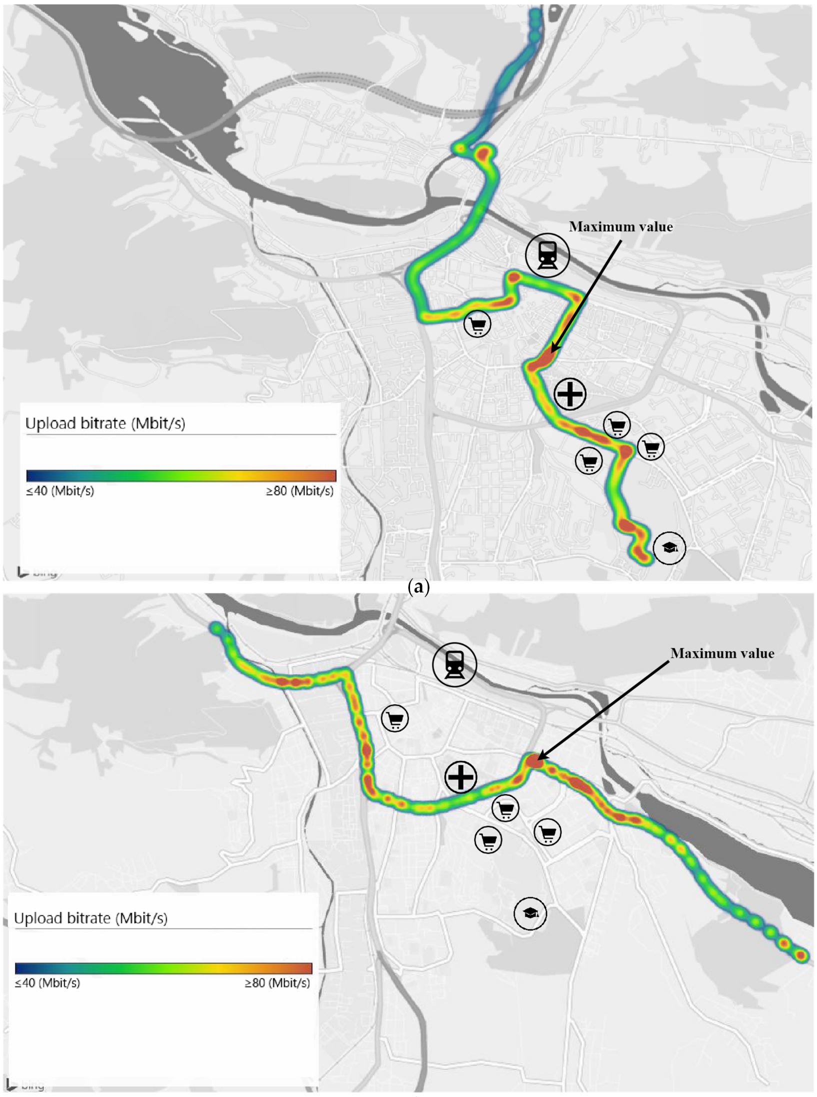
The analysis reveals that the network downlink speed is generally higher, particularly in urban areas represented by the red color. This can be attributed to the presence of multiple gNodeB support stations, which enhance the network throughput. However, in certain sections of route number 1, which passes through suburban areas, there is a significant drop in downlink speed represented by the turquoise color. This drop can be attributed to a much lower density of base stations serving the area. For illustration, the average density of base stations in suburban areas is less than one tenth of the average density of base stations in the urban area, according to the available base station location data. Therefore, a single gNodeB base station is serving a larger number of subscribers. The reduction in network bandwidth can be influenced by both network traffic and the number of base stations serving the network.

On route number 2, the generated heat map reveals a significant decrease in downlink speed in the area of the industrial zone, which is located on the right part of the Figure 4. This decrease can be observed as a change in color, indicating slower downlink speeds compared to other sections of the route. The decrease in downlink speed in the industrial zone can be attributed to the increased demand for downlink due to the large number of subscribers from the industrial zone. Industrial areas often have a high concentration of businesses and factories, resulting in a higher number of subscribers accessing the network simultaneously. The higher demand for downlink in the industrial zone puts strain on the network, leading to a decrease in individual downlink speeds. The limited capacity of the network to handle the increased demand in this specific area results in reduced network bandwidth and slower downlink speeds. The findings emphasize the need for optimizing network infrastructure in industrial zones to ensure efficient and reliable network performance. Strategies such as increasing network capacity and implementing advanced network management techniques can help address the increased demand for downlink in such areas. Further research and development in this area can lead to improvements in network capacity and ultimately enhance the connectivity and productivity of industrial zones in the 5G network.

4.2. Uplink

The uplink parameter is a crucial aspect of the 5G NSA system, as it determines the speed at which data are transmitted from user devices to the network. Understanding the variations in uplink speed along different routes can provide insights into network performance and optimize connectivity. In this part, we evaluate the uplink parameter on route number 1 and route number 2 in the 5G NSA system using heat map visualizations.

Figure 5 presents a heat map showing the average uplink of route 1 and route 2. The generated heat maps reveal interesting insights into the uplink parameter along route number 1 and route number 2. In general, the uplink speed is higher, especially in urban areas. This can be attributed to the presence of multiple base stations and improved network infrastructure in densely populated areas. Furthermore, maximal uplink speeds are observed near points of interest such as shopping centres, hospitals, and universities. These areas often experience higher demand for uplink speeds due to the large number of users and their data-intensive activities. The network infrastructure in these locations tends to be optimized by the network provider to cater for this demand, which often results in faster uplink speeds. This seems to be the case also for our area of interest, as can be observed by increased uplink speeds in Figure 5 and a higher concentration of base stations in the area, i.e., 6.5 base stations on average within 1 km and 3.5 base stations on average within 600 m of the point of interest. Taking into account the area, these numbers represent more than five times higher base station density near points of interest than is the city average. However, a significant decrease in uplink speed is observed in the suburban areas and the industrial zone. These areas are served by fewer base stations or a less optimized network infrastructure, leading to reduced uplink speeds. Additionally, the industrial zone may experience high network congestion due to the increased demand for uplink speeds from businesses and industries. Strategies such as increasing the number of base stations and implementing advanced network management techniques can help address the reduced uplink speeds in these areas. Further research and development in this area can lead to improvements in network capacity and ultimately enhance the overall performance of the uplink parameter in the 5G NSA system.



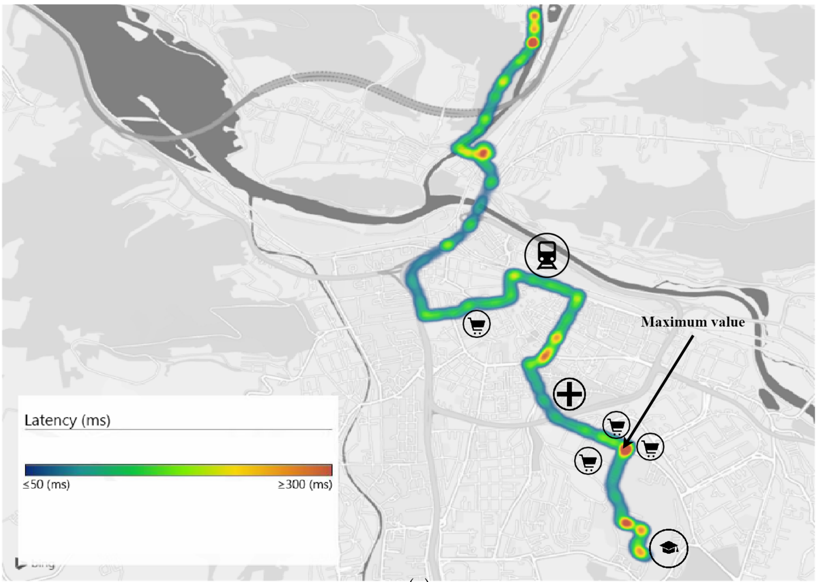
(b)

Figure 5. Average uplink speed on the route (**a**) number 1 and (**b**) number 2.

4.3. Latency

Two-way communication latency is a critical factor in the performance of the 5G network, especially in applications such as autonomous vehicles that rely on real-time data transmission. Understanding the variations in latency along different routes can provide insights into network performance and optimize communication efficiency. This part of the study aims to analyze the two-way communication latency on route number 1 and route number 2 in the 5G network using heat map visualizations.

In Figure 6, we can see a heat map that graphically shows the average of two-way communication latency on route 1 and route 2. The generated heat maps reveal notable insights into the two-way communication latency along route number 1 and route number 2. Several segments on the routes exhibit latency values exceeding 300 ms, which is considered high in terms of the technical requirements of autonomous vehicles. Higher latency is predominantly observed near points of interest and the industrial zone. These areas typically experience a large number of subscribers and internal management systems, leading to increased latency. The density of users and network congestion in these areas may contribute to higher latency values and reduced speeds. In contrast, significantly lower latency is observed outside the points of interest and the industrial zone. This segment is represented by the turquoise color on the route. The lower latency in these areas can be attributed to factors such as lower user density and reduced network congestion. The increased latency in certain areas may be caused by a large number of subscribers and the internal management system. The higher latency and lower throughput experienced near points of interest and the industrial zone of Zilina could be attributed to various factors. The density of users and network congestion in these areas may lead to increased latency and reduced speeds. Additionally, physical obstacles, such as buildings and infrastructure, could impact signal propagation and hinder network performance. These findings highlight the need for further optimization efforts and infrastructure enhancements to ensure reliable and efficient 5G connectivity in critical areas for autonomous mobility.



(**a**)

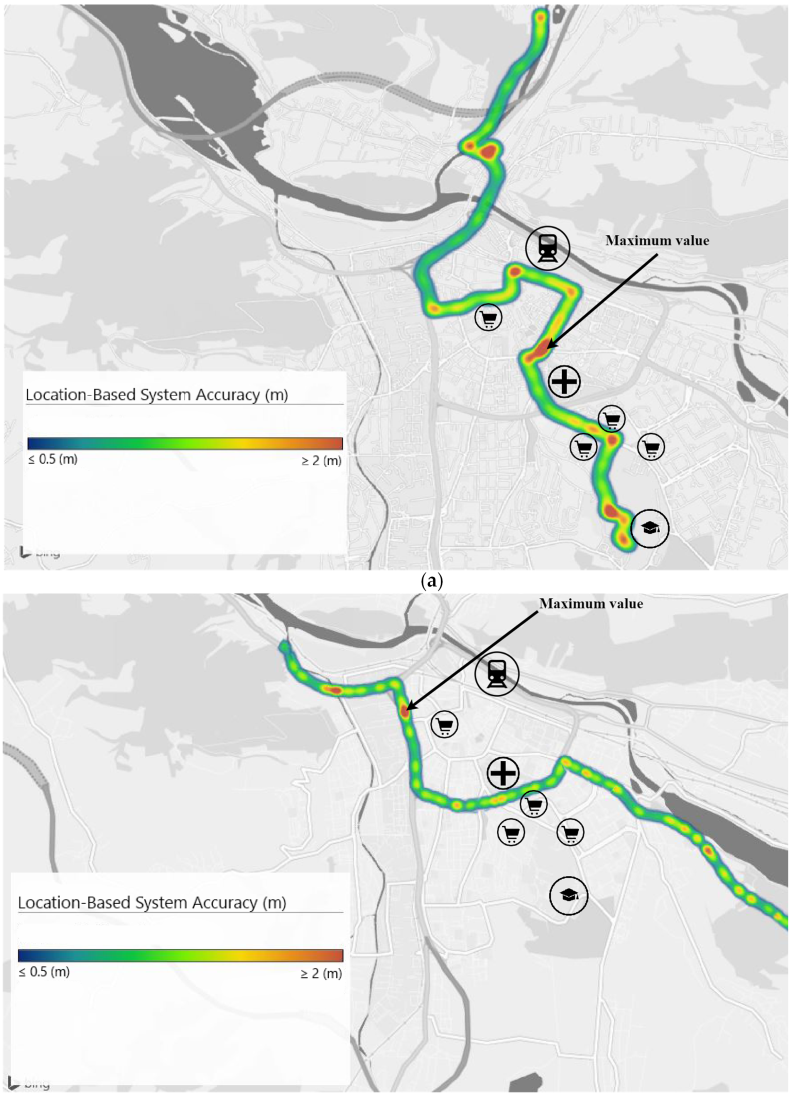
(**b**)

Figure 6. Average communication latency on the route (**a**) number 1 (**b**) and number 2.

Strategies such as increasing network capacity, implementing advanced traffic management techniques, and enhancing communication protocols can help address the higher latency and improve the overall performance of the 5G network. Further research and development in this area can lead to improvements in latency and throughput, ultimately enhancing the reliability and efficiency of communication in the 5G network.

4.4. Localization

Localization accuracy plays a crucial role in the performance of autonomous vehicles, as it determines their ability to accurately navigate and make informed decisions. Understanding the variations in localization accuracy along different routes is essential for optimizing autonomous vehicle operations. This study aims to analyze the localization accuracy on route number 1 and route number 2, considering the potential implementation of the Android Software Development Kit (SDK) in autonomous vehicles. The localization accuracy can be influenced by the internal interface of the used measurement device, such as the Android SDK. As this operating system is being implemented in vehicles and potentially in autonomous vehicles, it is crucial to represent these results. Heat map visualizations are utilized to graphically represent the average localization accuracy along these routes. The analysis reveals segments where the localization accuracy exceeds 2 m. Reduced localization accuracy is observed in dense areas, characterized by high buildings and dense vegetation. Conversely, higher localization accuracy is observed outside these areas. The results suggest the need for improved localization accuracy in specific route segments, which can be achieved through the integration of RTK technology. As can be seen in Figure 7 the analysis indicates that the localization accuracy on route number 2 is generally better compared to route number 1.



(b)

Figure 7. Average localization accuracy on route (**a**) number 1 and (**b**) number 2.

The generated heat maps reveal important insights into the localization accuracy for autonomous vehicles on route number 1 and route number 2. Several segments on the routes exhibit localization accuracy values exceeding 2 m, indicating reduced accuracy in these areas. The data points with very low location accuracy were consistently measured in urban canyons with average height of buildings above 12 m and an average width of less than 12 m. Similarly, reduced location accuracy was observed on road segments lined with thick vegetation with an average height of more than 10 m. These environments pose challenges for accurately calculating localization due to obstructed line-of-sight and signal interference. As a result, the localization accuracy in these segments is compromised. Conversely, higher localization accuracy is noticed outside the densely built or forested areas. The open nature of these segments allows for better line-of-sight and reduced signal interference, leading to improved localization accuracy. Based on the presented maps, it can be concluded that certain route segments require enhanced support in terms of localization accuracy. Furthermore, the analysis indicates that the localization accuracy on route number 2 is generally better compared to route number 1.

4.5. System Methodology for Detection of Readiness Status of Digital Infrastructure

Automated driving can safely work only in specific Operational Design Domains (ODDs) [35]. Furthermore, many works, such as [36–38] stress the importance of real-time data exchange capability for full materialization of all the expected CCAM benefits. Therefore, digital infrastructure is one of the main parameters in the design of CCAM. Preparing the infrastructure for automated driving is a major challenge, including parameters such as communication, provision of location, and mapping services, including machine-readable road markings and road geometry [39,40]. In this chapter, we would like to provide an example of a practical application of the proposed methodology. The proposed methodology can be used for a comprehensive system that will help operators evaluate the state of digital infrastructure in terms of its readiness for CCAM technology.

In order to ensure the successful deployment of autonomous services, it is crucial to establish a robust methodology (see Figure 8) capable of effectively comparing measured data against the requirements previously mentioned in Section 2.1. These requirements encompass mainly downlink, uplink, position accuracy, and latency, all of which are essential for the optimal functioning of autonomous systems. Given the vast volume of data encompassing hundreds of entries corresponding to multiple requirements, by establishing a reliable framework for data comparison, we can effectively gauge the extent to which autonomous services meet the specified requirements, while also keeping track of locations where the route was not able to provide the required level of performance. We needed to create an evaluation system that was straightforward in its function, while also being modifiable in real time. For this task, we chose MATLAB as the programming language and environment.

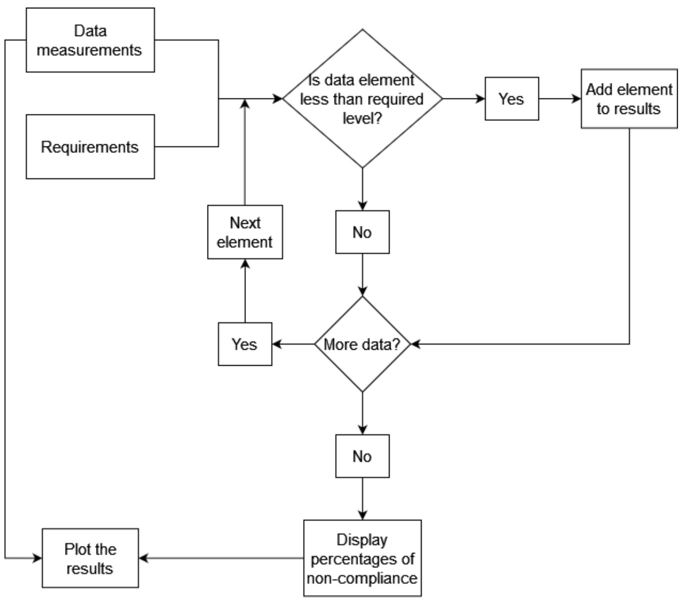


Figure 8. Non-Compliance Calculation and Visualization Flowchart.

Each requirement, service, and data measurement is loaded into separate entities, named after the corresponding measurements or requirements, to establish a clear and organized structure for managing and referencing the data. Next, our MATLAB code performs calculations and analysis on data, compares them, and calculates the percentage of non-compliance for each requirement. The results are then stored in variables and displayed in a table, as seen in Table 2, which includes a color code for quick interpretation. Red indicates non-compliance results (above 3%), indicating a failure. Yellow represents non-compliance values above 2% but below 3%, and green signifies a perfect score of 0% to 1%. The green highlighted services show good results in requirements and can be provided by the measured network.

Table 2. Percentage of non-compliance for each requirement for route number 1.

Service	Downlink	Uplink	Latency	Location Accuracy
Software Update	99.90%	0.00%	0.00%	0.00%
Traffic Jam Warning	0.00%	0.00%	0.11%	0.00%
Real-Time situational Awareness	0.00%	0.00%	100.00%	82.08%
Continuous Traffic Flow via Green Light Coordination	0.00%	0.00%	17.74%	82.08%
Automated Intersection Crossing	0.00%	0.00%	100.00%	100.00%
Security credentials	0.00%	0.00%	0.00%	0.00%
Bus Lane Sharing Request	0.00%	0.00%	6.24%	82.08%
Bus Lane Sharing Revoke	0.00%	0.00%	17.74%	82.08%
Speed harmonisation	0.00%	0.00%	0.22%	82.08%
Software Update of Reconfigurable Radio System	0.00%	0.00%	0.00%	0.00%
Tele-Operated Driving for Automated Parking	0.00%	12.68%	17.74%	100.00%
Vehicle Shares Information on Road Hazards/ Events	0.00%	0.00%	0.00%	0.00%
Vulnerable Road User (VRU)	1.00%	0.00%	17.74%	100.00%
Group Start	0.00%	0.00%	100.00%	100.00%
Tele-Operated Driving	0.00%	12.68%	17.74%	100.00%
Tele-Operated Driving Support	0.00%	12.68%	17.74%	100.00%
Obstructed View Assist	0.10%	0.00%	100.00%	8.12%
Remote Automated Driving Cancellation (RADC)	0.00%	0.00%	17.74%	0.00%
High-Definition Map Collecting and Sharing	0.37%	25.14%	17.74%	100.00%
In-Vehicle Entertainment (IVE)	97.52%	0.00%	100.00%	0.00%
Vehicle Platooning in Steady State	0.00%	0.00%	100.00%	100.00%
Autonomous Vehicle Disengagement Report	0.00%	5.61%	0.00%	82.08%
Law Enforcement Messaging	0.00%	0.00%	0.00%	0.00%
Patient Transport Monitoring	0.00%	0.31%	9.64%	0.00%
Accident report	0.00%	0.00%	0.00%	82.08%
Infrastructure Assisted Environment Perception	0.05%	100.00%	17.74%	100.00%
Infrastructure Based Tele-Operated Driving	0.00%	12.68%	100.00%	100.00%
Automated Valet Parking: Joint Authentication and Proof of Localisation	0.00%	0.00%	2.19%	82.08%
Automated Valet Parking: Wake-up	0.00%	0.00%	2.19%	82.08%
Awareness Confirmation	0.00%	0.00%	100.00%	82.08%
Cooperative Curbside Management	0.00%	0.00%	17.74%	100.00%

Red color indicates non-compliance results (above 3%). Yellow color represents non-compliance values above 2% but below 3%. Green color signifies a perfect score of 0% to 1%.

Finally, the code plots the measured values over time using a tiled layout. This visual representation depicts the trajectory of the measured values over time, incorporating explicit markers to indicate instances where the values failed to satisfy the corresponding requirement thresholds. Each requirement has its own plot, and the corresponding label is displayed. The x-axis represents the measurement points, and the y-axis represents the amplitude; for example in the case of downlink, it represents bitrate speeds in Mbit/s, as can be seen in Figure 9. By utilizing the amalgamation of numeric and graphical representations, we can identify specific sections within a route that require intervention to effectively support CCAM services. This comprehensive approach enables us to generate informative heat maps, highlighting areas where the communication technology fails to meet the minimum requirements, thus providing insights into underserved sections requiring attention and optimization. Orange circles represent visual representation of points in which the download speed was not able to fulfill the requirements of a service Vulnerable Road User (VRU).

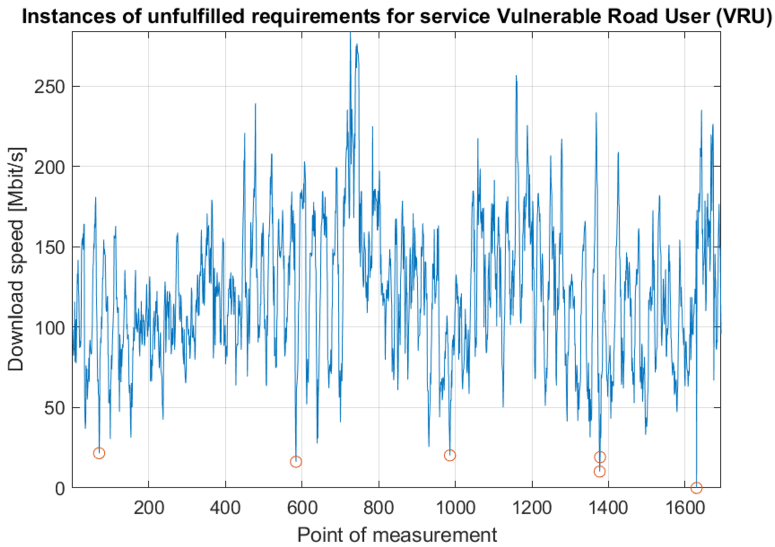


Figure 9. Visual representation of points in which downlink speeds do not meet the requirements of a service Vulnerable Road User (VRU).

The results obtained through this code demonstrate its capability as a proof of concept for future real-time data analysis, providing valuable insights into the performance of digital infrastructure. The code and the results it generated have already served as a basis for additional research efforts. Notably, they have been utilized in identifying correlations between route parameter measurements taken at different times and assessing the stability of the examined parameters across time.

4.6. Identification of Underserved Segments

The successful integration of autonomous mobility relies on robust and high-performing communication networks, such as 5G, to ensure seamless data exchange and real-time decision-making. This study focuses on evaluating underserved sections within the 5G network along a specific routes. The objective is to identify areas that may require further optimization to meet the communication requirements of autonomous vehicles. Our research on the underserved sections of Zilina's 5G network emphasizes the importance of addressing performance limitations to ensure the readiness of autonomous mobility. The identified underserved sections in terms of latency, uplink speed, and downlink speed indicate areas that require further optimization to meet the communication requirements of autonomous vehicles. By addressing these challenges through infrastructure enhancements and network optimizations, Zilina can pave the way for a reliable and efficient 5G network that fully supports the communication requirements of autonomous mobility. Based on the developed methodology in combination with the evaluation system, we focused on the identification of underserved route sections in terms of unmet service requirements. This allows us to find route sections that require intervention to support a specific CCAM service. For the interpretation, we chose the advanced Tele-Operated Driving Service (see Table 2). As Table shows, the communication technology does not meet the minimum requirements in terms of latency for 17.74% of the examined route number 1, in terms of uplink speed for 12.67% of the route, and in terms of localization accuracy for 100% of the route. In Figures 10 and 11, we can see the map in which the red dots show the underserved sections in terms of the latency parameter on Route 1 and Route 2.

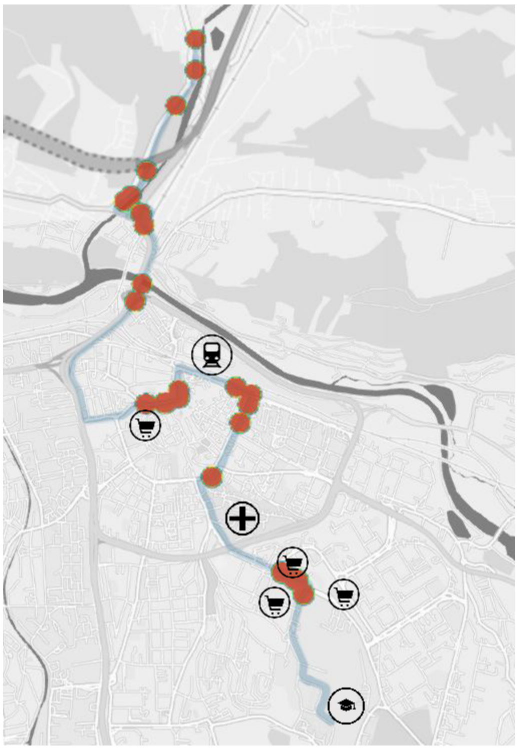


Figure 10. Identification of underserved sections in terms of latency on Route 1.

The analysis reveals that the underserved sections in terms of latency for the Tele-Operated Driving service are primarily found in areas with a large number of subscribers, including suburban and industrial areas. These sections would not be able to adequately support the service due to the high latency values.

Figure 11. Identification of underserved sections in terms of latency on Route 2.

Figure 12 showcases the underserved sections in terms of latency on Route 1, while Figure 13 represents the underserved sections on Route 2. Furthermore, underserved sections in terms of uplink speed are also identified on Route 1 and Route 2. These sections indicate areas where the uplink speed does not meet the minimum requirements for the Tele-Operated Driving service. The lack of sufficient uplink speed can hinder real-time data exchange and decision-making. The underserved sections in terms of uplink speed on Route 1 and Route 2 are visualized in Figures 12 and 13.

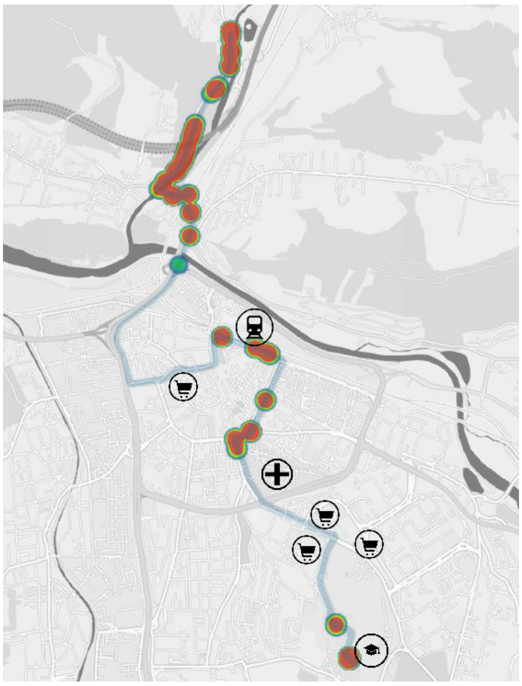


Figure 12. Identification of underserved sections in terms of uplink on Route 1.

Figure 13. Identification of underserved sections in terms of uplink on Route 2.

As can be seen, most of the underserved sections in terms of uplink speed are mainly located in the suburban area. We note that these areas are also problematic in terms of several parameters. In terms of localization accuracy, we do not interpret the underserved sections because both routes are underserved by 100%.

Based on the identification of the underserved segments, we can determine which segments of the route should be improved in the telecommunication system in order to support the operation of the services. Identifying underserved segments is an important process by which we can help telecommunications companies improve network performance by upgrading these segments. Through this, operating companies can avoid investing in unnecessary upgrades in other areas of the network. The analysis of underserved sections emphasizes the need for further optimization. The underserved sections in terms of latency and uplink speed are mainly located in areas with a large number of subscribers, including suburban and industrial areas. Addressing these underserved sections through infrastructure enhancements and network optimizations is crucial to ensure a reliable and efficient 5G network that fully supports the communication requirements of autonomous mobility.

5. Discussion and Conclusions

The readiness of 5G networks for autonomous mobility is crucial for the safe and efficient operation of autonomous vehicles. The proposed frameworks and system help to identify gaps in infrastructure that could be safety risks for CAVs, while also identifying areas of infrastructure that are not optimised for CAVs, such as intersections or city centres. Based on our research, we conclude that research on telecommunication network parameters has shown that these parameters are not stable. Our research highlights the vulnerability of telecommunication networks to factors such as network traffic, environmental conditions, and hardware limitations. Understanding and mitigating the instability of these parameters is crucial for ensuring the reliable and efficient operation of telecommunication networks, particularly in the context of CCAM deployments. Continued research and development efforts are necessary to optimize network performance, reduce latency, and enhance the overall quality of service for autonomous mobility applications.

Latency is a major problem in the area of communication. During our research, we identified segments that are critical for the operation of CCAM services in terms of latency. These are mainly located at intersections with heavy traffic or close to points of interest. The traffic safety services provided by CCAM have strict latency requirements; these can only be met through ultra-low latency and reliable connectivity. This is the primary goal of URLLC (Ultra Reliable, Low-Latency Communications) technology, which can be provided by 5G SA technology. The current 5G NSA technology provides only some of the main benefits of 5G SA networks, such as the high data rate. By building standalone 5G SA systems, operators are expected to discard the 5G NSA technology used so far. Based on this, we state that the best solution to accelerate the implementation of CCAM is the deployment of 5G SA networks. The current construction of 5G NSA networks is focused on high-population-density areas. Standalone 5G SA networks represent a new area for experimental research just from the CCAM readiness perspective while researchers can use our evaluation framework, data, and methodology. To solve the problem of parameter fluctuation, continued research and development of technologies that can support and improve the stability of telecommunication networks is needed. This includes, for example, the development of advanced hardware and software solutions that can better manage network traffic. Research on monitoring and management tools can help network operators identify and address issues that can affect the stability of telecommunications networks. The identified issues in latency and throughput near points of interest and the industrial zone in Zilina city indicate the necessity for network improvements to meet the communication demands of autonomous vehicles in these areas. Future research should focus on addressing the specific challenges identified, including network optimization, expanding coverage, and reducing latency to ensure seamless and reliable connectivity for autonomous mobility applications. Furthermore, in-depth research on the impact of factors affecting the network performance, such as the density of users and related network traffic, environmental conditions, and hardware limitations is necessary to better understand and quantify their effect on the CCAM readiness of the digital infrastructure. Our research on the latency and throughput of the 5G network in Zilina highlights the need for further improvements to support the readiness of autonomous mobility. The higher latency and lower speeds observed near points of interest and the industrial zone emphasize the importance of optimizing 5G network performance in these critical areas. Addressing these challenges will be crucial for enabling real-time data exchange and decision-making, and ensuring the safe and efficient operation of autonomous vehicles in Zilina and similar urban environments. The identification of underserved sections within Zilina's 5G network highlights the need for further optimization and infrastructure enhancements to support autonomous mobility. Addressing the latency, upload speed, and download speed limitations in these sections is crucial for enabling seamless communication and data exchange between autonomous vehicles and the surrounding infrastructure.

In terms of localization, we were able to identify areas where localization accuracy is low and reveal the effects on localization accuracy. By investigating the fluctuations in localization accuracy, we can verify the performance of localization systems and receiving devices and identify opportunities for improvement. A possible solution is the integration of 5G networks combined with GNSS and RTK technology, which can significantly improve the localization accuracy in built-up urban areas. At the same time, by combining GNSS, digital maps, and neural networks, the vehicle can recognise direction of travel, speed, lanes, and road signs. However, this presents further scope for research. Another area is the research and development of light signal detection, which the automotive industry is trying to develop at an increasingly rapid speed. We note that the deployment of CCAM technology will cause an extreme increase in data traffic with ever-increasing technical requirements on the communication infrastructure. B5G technologies present new technological opportunities in terms of high throughput using terahertz radio frequency bands. By integrating B5G technologies such as Mobile Edge Computing (MEC), Network Slicing, Software-Defined Networking (SDN), 5G New Radio (5GNR), blockchain, Federated Learning (FL), and Zero touch network and Service Management (ZSM), we can significantly optimize network parameters.

Author Contributions: Conceptualization, T.P., B.C. M.S. and P.K.; methodology, B.C., M.S. and T.P.; software, M.S., B.C. and T.P.; validation, T.P., P.K. and M.D.; formal analysis, T.P., B.C. and P.K.; investigation, B.C. and P.K.; resources, M.D.; data curation, B.C. and T.P.; writing—original draft preparation, T.P., B.C. and P.K.; visualization, T.P., P.K. and B.C.; supervision, M.D. and P.K.; project administration, M.D. and P.K.; funding acquisition, M.D., T.P. and P.K. All authors have read and agreed to the published version of the manuscript.

Funding: This publication was realized with support of Operational Program Integrated Infrastructure 2014–2020 of the project: Innovative Solutions for Propulsion, Power and Safety Components of Transport Vehicles, code ITMS 313011V334, co-financed by the European Regional Development Fund and by the Slovak Research and Development Agency under the project No. PP-COVID-20-0100: DOLORES.AI: The pandemic guard system.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

The following abbreviations are used in this manuscript:

5GNR	5G New Radio
CAVs	Connected and Automated Vehicles
CCAM	Connected and Cooperative Automated Mobility
C-ITS	Cooperative Intelligent Transport Systems

CQI	Channel Quality Indicator
CSV	Comma-Separated Values
C-V2X	Cellular Vehicle-to-Everything
DIQAS	Digital Infrastructure Quality Assessment System
DSRC	Dedicated Short-Range Communications
FL	Federated Learning
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
MEC	Mobile Edge Computing
NTP	Network Time Protocol
NSA	Non-Standalone
NR	New Radio
ODDs	Operational Design Domains
PC5	Sidelink interface in cellular networks
PDR	Packet Delivery Ratio
QoS	Quality of Service
RTK	Real-Time Kinematic
RSRP	Reference Signal Receive Power
RSRQ	Reference Signal Receive Quality
SA	Standalone
SDN	Software-Defined Networking
SDK	Software Development Kit
SNR	Signal-to-Noise Ratio
URLLC	Ultra Reliable, Low Latency Communications
V2N	Vehicle-to-Network
V2P	Vehicle-to-Pedestrian
V2X	Vehicle-to-Everything
ZSM	Zero touch network and Service Management

Appendix A. Communication and Localization Requirements of Common V2N C-ITS Services

Table A1. Communication and localization requirements of basic V2N C-ITS services.

3GPP Rel.	Service	Uplink [Kbit/s]	Downlink [Kbit/s]	Latency [ms]	Position Accuracy [m]	Message Generation Frequency and Type	Service Level Reliability [%]
8	Software Update [26]	-	300,000	N/A	30	-	N/A
14	Traffic Jam Warning [26]	24	24	2000	<20	N/A (DENM/BSM)	50%
	Real Time situational Awareness [26]	8	8	20	1.5	10 Hz (CAM/BSM)	99%
	Continuous Traffic Flow via Green Light Coordination [29]	48	2.4	100	1.5	20 Hz Uplink (CAM/BSM), 1 Hz Downlink (CAM/BSM/ DENM)	95%
	Automated Intersection Crossing [29]	8.8	8.8	10	0.15	10 Hz (CAM/BSM)	99.9999%
	Security credentials [29]	300 kB per month	300 kB per month	N/A	-	-	N/A%

Table A2. Communication and localization requirements of advanced V2N C-ITS services.

3GPP Rel.	Service	Uplink [Kbit/s]	Downlink [Kbit/s]	Latency [ms]	Position Accuracy [m]	Message Generation Frequency and Type	Service Level Reliability [%]
12	Bus Lane Request [29]	40	40	200	1.5	N/A (DENM)	99%
	Bus Lane Revoke [29]	48	48	100	1.5	20 Hz (CAM/BSM)	95%
14	Speed harmonisation [26]	6	6	1400	1.5	N/A (DENM)	80%
	SW Update of Re-configurable Radio System [26]	-	440	N/A	30	N/A	99%
15	Tele-Operated Driving for Automated Parking * [26]	36,000	400	100	0.1	N/A	-
	Vehicle Shares Information on Road Hazards/Events * [26]	120	120	-	-	-	-
16	Vulnerable Road User (VRU) [26]	-	24,000 initially, 2000 periodically	100	0.2	10 Hz (VAM) per VRU	99.9%
	Group Start [29]	40	40	10	0.2	20 Hz (CAM)	99.999%
	Tele-Operated Driving [29]	36,000	400	100 Downlink, 20 Uplink	0.1	50 Hz (Downlink command message)	Uplink: 99%, Downlink: 99.999%
	Obstructed View Assist [29]	-	5000	50	2	video streaming	99%
	Remote Automated Driving Cancellation [29]	-	0.048	100	10	0.02 Hz (handshake)	99.999%
	High-Definition Map Collecting and Sharing [29]	47,000	16,000	100	0.5	-	99%
	In-Vehicle Entertainment [29]	-	250,000	20	30	Varies depending on service	99%
	Autonomous Vehicle Disengagement Report [29]	27,000	-	Est. 10 min	1.5	-	99.9%
	Patient Transport Monitoring [29]	9000	-	150	N/A	Video, data and audio streaming	99.999% for data stream
16	Accident Report * [29]	1800	-	-	1.5	N/A Sensor data prior to and after the collision	99.99%
	Tele-Operated Driving Support [29]	36,000	400	100 Downlink, 20 Uplink	0.1	50 Hz (Downlink command message)	Uplink: 99%, Downlink: 99.999%
	Vehicle Platooning in Steady State * [29]	8	8	50	0.5	10 Hz (100 Bytes)	99.9%
	Law Enforcement Messaging [29]	24	24	100	-	-	-
	Infrastructure Assisted Environment Perception [29]	70,000–155,000	4000	100	0.1	-	99.99%
	Infrastructure Based Tele-Operated Driving [29]	36,000	400	50	0.1	50 Hz (DL Command message)	99.999%
	Automated Valet Parking: Joint Authentication and Proof of Localisation [29]	16	16	500	1.5	1000 bytes in 500 ms	99%
	Automated Valet Parking: Wake-up [29]	3.2	3.2	500	1.5	N/A	99%
	Awareness Confirmation [29]	40	40	20	1.5	50 Hz	99.9%
	Cooperative Curbside Management [29]	64	64	100	1	-	99.9%

* The service may have variations requiring higher 3GPP Release features.

References

1. European Commission. Cooperative, Connected and Automated Mobility (CCAM). Available online: https://transport.ec.europa.eu/transport-themes/intelligent-transport-systems/cooperative-connected-and-automated-mobility-ccam_en (accessed on 10 July 2023.
2. Vukadinovic, V.; Bakowski, K.; Marsch, P.; Garcia, I.D.; Xu, H.; Sybis, M.; Sroka, P.; Wesolowski, K.; Lister, D.; Thibault, I. 3GPP C-V2X and IEEE 802.11p for Vehicle-to-Vehicle communications in highway platooning scenarios. *Ad Hoc Netw.* **2018**, *74*, 17–29. [CrossRef]
3. Molina-Masegosa, R.; Gozalvez, J. LTE-V for Sidelink 5G V2X Vehicular Communications: A New 5G Technology for Short-Range Vehicle-to-Everything Communications. *IEEE Veh. Technol. Mag.* **2017**, *12*, 30–39. [CrossRef]
4. Bazzi, A.; Masini, B.M.; Zanella, A.; Thibault, I. On the Performance of IEEE 802.11p and LTE-V2V for the Cooperative Awareness of Connected Vehicles. *IEEE Trans. Veh. Technol.* **2017**, *66*, 10419–10432. [CrossRef]
5. Tseng, Y.L. LTE-Advanced enhancement for vehicular communication. *IEEE Wirel. Commun.* **2015**, *22*, 4–7. [CrossRef]
6. Sempere-García, D.; Sepulcre, M.; Gozalvez, J. LTE-V2X Mode 3 scheduling based on adaptive spatial reuse of radio resources. *Ad Hoc Netw.* **2021**, *113*, 102351. [CrossRef]
7. Soto, I.; Calderon, M.; Amador, O.; Urueña, M. A survey on road safety and traffic efficiency vehicular applications based on C-V2X technologies. *Veh. Commun.* **2022**, *33*, 100428. [CrossRef]
8. Garcia, M.H.C.; Molina-Galan, A.; Boban, M.; Gozalvez, J.; Coll-Perales, B.; Şahin, T.; Kousaridas, A. A Tutorial on 5G NR V2X Communications. *IEEE Commun. Surv. Tutorials* **2021**, *23*, 1972–2026. [CrossRef]
9. Gonzalez-Martín, M.; Sepulcre, M.; Molina-Masegosa, R.; Gozalvez, J. Analytical Models of the Performance of C-V2X Mode 4 Vehicular Communications. *IEEE Trans. Veh. Technol.* **2019**, *68*, 1155–1166. [CrossRef]
10. 3rd Generation Partnership Project (3GPP), Technical Specification Group Radio Access Network; Overall Description of Radio Access Network (RAN) Aspects for Vehicle-to-Everything (V2X) Based on LTE and NR (Release 16), 3GPP TR 37.985 V16.0.0, June 2020. Available online: https://portal.3gpp.org/desktopmodules/Specifications/SpecificationDetails.aspx?specificationId=3601 (accessed on 22 August 2023).
11. Farsimadan, E.; Palmieri, F.; Moradi, L.; Conte, D.; Paternoster, B. Vehicle-to-Everything (V2X) Communication Scenarios for Vehicular Ad-hoc Networking (VANET): An Overview. In Proceedings of the Computational Science and Its Applications—ICCSA 2021, Cagliari, Italy, 13–16 September 2021; Gervasi, O., Murgante, B., Misra, S., Garau, C., Blečić, I., Taniar, D., Apduhan, B.O., Rocha, A.M.A.C., Tarantino, E., Torre, C.M., Eds.; Springer International Publishing: Cham, Switzerland, 2021; pp. 15–30.
12. Storck, C.R.; Duarte-Figueiredo, F. A Survey of 5G Technology Evolution, Standards, and Infrastructure Associated with Vehicle-to-Everything Communications by Internet of Vehicles. *IEEE Access* **2020**, *8*, 117593–117614. [CrossRef]
13. Hussein, A.; García, F.; Armingol, J.M.; Olaverri-Monreal, C. P2V and V2P communication for Pedestrian warning on the basis of Autonomous Vehicles. In Proceedings of the 2016 IEEE 19th International Conference on Intelligent Transportation Systems (ITSC), Rio de Janeiro, Brazil, 1–4 November 2016; pp. 2034–2039. [CrossRef]
14. Bagheri, M.; Siekkinen, M.; Nurminen, J.K. Cellular-based vehicle to pedestrian (V2P) adaptive communication for collision avoidance. In Proceedings of the 2014 International Conference on Connected Vehicles and Expo (ICCVE), Vienna, Austria, 3–7 November 2014; pp. 450–456. [CrossRef]
15. Li, C.Y.; Salinas, G.; Huang, P.H.; Tu, G.H.; Hsu, G.H.; Hsieh, T.Y. V2PSense: Enabling Cellular-Based V2P Collision Warning Service through Mobile Sensing. In Proceedings of the 2018 IEEE International Conference on Communications (ICC), Kansas City, MO, USA, 20–24 May 2018; pp. 1–6. [CrossRef]
16. Chen, Q.; Tang, S.; Hochstetler, J.; Guo, J.; Li, Y.; Xiong, J.; Yang, Q.; Fu, S. Low-Latency High-Level Data Sharing for Connected and Autonomous Vehicular Networks. In Proceedings of the 2019 IEEE International Conference on Industrial Internet (ICII), Orlando, FL, USA, 11–12 November 2019; pp. 287–296. [CrossRef]
17. Naudts, D.; Maglogiannis, V.; Hadiwardoyo, S.; van den Akker, D.; Vanneste, S.; Mercelis, S.; Hellinckx, P.; Lannoo, B.; Marquez-Barja, J.; Moerman, I. Vehicular Communication Management Framework: A Flexible Hybrid Connectivity Platform for CCAM Services. *Future Internet* **2021**, *13*, 81. [CrossRef]
18. Chiha, A.; Denis, B.; Verbrugge, S.; Colle, D. Techno-Economic Analysis of MEC Clustering Models for Seamless CCAM Service Provision. *IEEE Commun. Mag.* **2023**, *61*, 32–37. [CrossRef]
19. Kousaridas, A.; Fallgren, M.; Fischer, E.; Moscatelli, F.; Vilalta, R.; Mühleisen, M.; Barmpounakis, S.; Vilajosana, X.; Euler, S.; Tossou, B.; et al. 5G Vehicle-to-Everything Services in Cross-Border Environments: Standardization and Challenges. *IEEE Commun. Stand. Mag.* **2021**, *5*, 22–30. [CrossRef]
20. Hofbauer, F.; Walch, M.; Schildorfer, W.; Neubauer, M. Towards Requirements Related to Future CCAM Services for Road Usage Optimization. In Proceedings of the Human Interaction, Emerging Technologies and Future Systems V, Paris, France, 27–29 August 2021; Springer International Publishing: Cham, Switzerland, 2022; pp. 1294–1301.
21. Lin, X. An Overview of 5G Advanced Evolution in 3GPP Release 18. *IEEE Commun. Stand. Mag.* **2022**, *6*, 77–83. [CrossRef]
22. Chen, S.; Hu, J.; Shi, Y.; Peng, Y.; Fang, J.; Zhao, R.; Zhao, L. Vehicle-to-Everything (v2x) Services Supported by LTE-Based Systems and 5G. *IEEE Commun. Stand. Mag.* **2017**, *1*, 70–76. [CrossRef]
23. 5GAA Automotive Association. *List of C-V2X Devices*; 5G Automotive Association: Munich, Germany, 2021.

24. Cinque, E.; Valentini, F.; Persia, A.; Chiocchio, S.; Santucci, F.; Pratesi, M. V2X Communication Technologies and Service Requirements for Connected and Autonomous Driving. In Proceedings of the 2020 AEIT International Conference of Electrical and Electronic Technologies for Automotive (AEIT AUTOMOTIVE), Turin, Italy, 18–20 November 2020; pp. 1–6. [CrossRef]
25. Boban, M.; Kousaridas, A.; Manolakis, K.; Eichinger, J.; Xu, W. Use Cases, Requirements, and Design Considerations for 5G V2X. *IEEE Veh. Technol. Mag.* **2018**., *13*, 110–123. [CrossRef]
26. 5GAA Automotive Association. *C-V2X Use Cases and Service Level Requirements Volume I*; Technical Report; 5G Automotive Association: Munich, Germany, 2023.
27. Arpitha, H.S.; Anand, K.R. Designing, Dimensioning and Testing SDN-NFV Private Cloud Architecture based realisation of 5GC with IIOT, MCS, CV2X and VONR Service. In Proceedings of the 2022 IEEE Wireless Antenna and Microwave Symposium (WAMS 2022), Rourkela, India, 5–8 June 2022.
28. Wang, D.; Sattiraju, R.R.; Qiu, A.; Partani, S.; Schotten, H.D. Effect of Retransmissions on the Performance of C-V2X Communication for 5G. In Proceedings of the 2020 IEEE 92nd Vehicular Technology Conference (VTC2020-Fall), Virtual, 18 November–16 December 2020. [CrossRef]
29. 5GAA Automotive Association. *C-V2X Use Cases Volume II: Examples and Service Level Requirements*; White Paper; 5G Automotive Association: Munich, Germany, 2020.
30. 3GPP. 3GPP Release 12. 2021. Available online: https://www.3gpp.org/specifications-technologies/releases/release-12 (accessed on 22 August 2023).
31. 3GPP. 3GPP Release 14. 2021. Available online: https://www.3gpp.org/specifications-technologies/releases/release-14 (accessed on 22 August 2023).
32. 3GPP. 3GPP Release 15. 2021. Available online: https://www.3gpp.org/release-15 (accessed on 23 August 2023).
33. 3GPP. 3GPP Release 16. 2021. Available online: https://www.3gpp.org/release-16 (accessed on 23 August 2023).
34. Cucor, B.; Petrov, T.; Kamencay, P.; Pourhashem, G.; Dado, M. Physical and Digital Infrastructure Readiness Index for Connected and Automated Vehicles. *Sensors* **2022**, *22*, 7315. [CrossRef] [PubMed]
35. Alessandrini, A.; Domenichini, L.; Branzi, V. Chapter 7-Infrastructures to accommodate automated driving. In *The Role of Infrastructure for a Safe Transition to Automated Driving*; Alessandrini, A., Domenichini, L., Branzi, V., Eds.; Elsevier: Amsterdam, The Netherlands, 2021; pp. 237–366. [CrossRef]
36. Hetzer, D.; Muehleisen, M.; Kousaridas, A.; Barmpounakis, S.; Wendt, S.; Eckert, K.; Schimpe, A.; Löfhede, J.; Alonso-Zarate, J. 5G connected and automated driving: Use cases, technologies and trials in cross-border environments. *EURASIP J. Wirel. Commun. Netw.* **2021**, *2021*, 97. [CrossRef] [PubMed]
37. Almeida, J.; Ferreira, J.; Moutinho, J.; Jauregui, D.; Álvarez, E.; Sambeek, M. CCAM Infrastructure Support for 5G Advanced Driving Scenarios. In Proceedings of the Virtual ITS European Congress, Virtual, 9–10 November 2020.
38. Ferreira, J. *Cooperative Connected and Automated Mobility (CCAM)*; MDPI: Basel, Switzerland, 2020.
39. Parekh, D.; Poddar, N.; Rajpurkar, A.; Chahal, M.; Kumar, N.; Joshi, G.P.; Cho, W. A Review on Autonomous Vehicles: Progress, Methods and Challenges. *Electronics* **2022**, *11*, 2162. [CrossRef]
40. Rana, K.; Gupta, G.; Vaidya, P.; Tomar, A.; Kumar, N. Evolution of Autonomous Vehicle: An Artificial Intelligence Perspective. In Proceedings of International Conference on Recent Innovations in Computing: ICRIC 2022, Jammu, India, 13–14 May 2022; Springer: Singapore, 2023; pp. 71–81. [CrossRef]