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Special Issue on Robust, Safe, and Secure Implementation of Connected and Automated Vehicles' Functional Software Design and Architecture

Connected and automated driving in snowy and icy conditions – results of four field-testing activities carried out in Finland

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Abstract

Automated driving expected benefits, such as enhanced traffic safety, are only fully realized in the future when the vehicles are able to manoeuvre in all weather conditions. Finnish transport agencies and EU CEF-funded projects aim to study automated driving in icy and snowy conditions. The four studies on digital and physical infrastructure to support automated driving included post and poles, Cooperative Intelligent Transport Systems (C-ITS) hybrid communication, accurate positioning of vehicles and vehicle remote control using cellular communication. The results present a prototype of passive radar reflector, a C-ITS hybrid communication solution, and a reliable positioning system for an automated vehicle in Arctic north extreme weather conditions. During the tests, ITS-G5 provided more stable Infrastructure to Vehicle (I2V) communication than commercial 4G Long Term Evolution (LTE) but had more limited geographical coverage.

Keywords: Automated vehicle, autonomous driving, C-ITS hybrid communication, passive radar reflectors, radar systems, remote control

1. Introduction

Connected and automated driving is expected in Europe and globally to improve traffic safety and flow, reduce emissions, as well as enhance travel comfort and accessibility in future [1]. While SAE levels 1 and 2 of driving automation operate in roads today [2], higher levels of automated driving features and deployment require advance, for example, on in-vehicle technology, physical and digital infrastructure, big data and artificial intelligence, policies, societal and human factors as well as business models. Furthermore, the development is challenged by changing road conditions, e.g. rain, snow and ice. All year operation is required in order for connected and automated driving to reach its full potential and benefits in the future.

To overcome weather related challenges and enhance automated vehicle Operational Design Domain (ODD), i.e. operational conditions that it is designed to function, road testing in different weather conditions is required [3]. This study aims to present four different physical and digital infrastructure activities key results on automated and connected driving in arctic weather conditions. First, requirements for posts and poles embedded into roadside infrastructure, the type, location and characteristics of the landmarks, such as delineators and reflective posts, or snow poles and plot access marks that could support automated driving. Second, C-ITS hybrid communication, i.e.in this study 4G Long Term Evolution (LTE) cellular communication as well as European Telecommunications Standards Institute (ETSI) ITS-G5 (IEEE 802.11). Third, accurate positioning of vehicles in Arctic latitudes and on roads covered with snow and/or ice. Fourth, vehicle remote control using cellular communication.

2. Methodology

Aim of the study was to review available and new solutions for connected and automated driving issues in arctic weather conditions. The study activities of physical infrastructure, communications, location data and positioning as well as remote driving were established from the Finnish road transport authorities published Road Transport Automation Road Map and Action Plan 2016–2020 study report. The Road Map and Action Plan aim was to fill in knowledge gaps and give guidance on connected and automated driving planning and implementation process for the authorities. [4]

Finnish authorities arranged an open market dialogue, which results were used as a basis for a procurement call. Three industry consortiums were awarded including fifteen partners of data and service providers, equipment manufacturers, network providers, research centers and universities. Each coalition member selected the most suitable method to conduct data collection and analysis for the study activity.

Quantitative methods were used in three studies analyses: radar signal and passive radar reflectors, commercial cellular network latency, and vehicle positioning. Qualitative analysis was performed for the autonomous vehicle (AV) remote control intervention, based on the measured vehicle trajectory, and partly for the Cooperative ITS hybrid communication selected Day 1 messages performance. Quantitative methods were preferred to enhance reliability and validity of the results, e.g. repeatability of the measurements. Qualitative methods were used in addition at those cases where number of measurements were low and human operator was present (remote control) as well as when quantitative results indicated inaccuracies (C-ITS messages). The data collections were performed in specific field tests; the collected data amounts were limited and therefore further tests in future with quantitative methods as well as different winter weather environments would enhance reliability and validity of the results.

Results of the study provide knowledge and guidance for the public authorities to further analyze infrastructure requirements for connected and automated driving in snowy and icy conditions.

3. Ethical considerations of the field tests

The industry coalitions implemented, among their own testing activities in different locations around Finland, three one-week collaborative field operation tests at the Aurora E8 test road section in Muonio in real-life traffic [5]. The aim of the three collaborative field tests was to verify the results in Arctic conditions. Part of the verifications were executed with automated vehicles. Finland’s current road traffic legislation permits automated vehicle trials. Finnish Transport and Communications Agency evaluated and granted the companies test plate certificates that entitled them to drive automated vehicles with test plates for one year from the date of the issue [6].

The public and private partners implemented a field test plan in collaboration to prepare test management. Each of the companies’ members attending the field test and working in the road section, were required to complete the Finnish road administration defined roadwork safety card level 1 and the project manager the level 2 card [7] [8]. Before each field test, the responsible company called a preparation meeting to plan the implementation and use of the road section to ensure road safety. Start of a field test was reported to authorities and local contractors via email two weeks beforehand. The contacts included road authority and contractors in the area with infrastructure responsibility, Northern Finland Traffic Management Centre (TMC) and the Lapland Centre for Economic Development, Transport, and the Environment.

Three main factors affecting road safety were reported by the companies: vehicles and heavy-trucks passing the automated vehicle, slow speed of the automated vehicles or speed difference with other traffic and poor weather conditions. Following four measures to minimize risks and improve road safety were taken. First, one of the companies used a safety car driving behind the automated vehicle to warn other drivers (Figure 1 b). Second, the TMC and authorities provided traffic management support with Variable Message Sign (VMS) (Figure 1 a) and by reducing speed limits in certain test section locations from 100 km/h to 80 km/h. Third, roadside shoulders and bus stops were considered important. The automated vehicle could pull on the side of the road due to pause in testing, letting other cars pass the test vehicle or even if technical malfunctions would occur. Fourth, national press release was published and communication and discussion event arranged for the local people.

Figure 1 (a) VMS (left) and (b) safety car (right) warning drivers of automated vehicles' field-testing in the test section. (Pictures: (a) left Risto Kulmala and (b) right Sensible 4)

4. Results

4.1. Posts and poles

Road transport is becoming increasingly automated [9], and autonomous driving vehicles could become the most important transformation in automobile industry in the current century [10]. In most of the cases, the high level of automation is greatly based on the positioning systems, such as GPS or 5th generation mobile communication system (5G), and the ability of the vehicle to sense its surroundings by utilising a set of sensors such as LiDAR, radars, ultrasonic sensors and cameras [11]. Hereby, an accurate and reliable detection of vessels and other objects such as physical land infrastructure is a challenging task for scientists and engineers. [12]

Most of the automated vehicle tests are currently carried out in snow-free areas. However, there are numerous challenges that arise in Finland and other Nordic countries when testing autonomous functions in snowy and icy road conditions. Drifting and blowing snow practically blocks the vision of any camera system while causing major difficulties for LiDAR systems as well. On snow-covered roads, the lane markings are not visible either. Further, the availability of satellite positioning is more limited in Arctic areas and magnetic storms, i.e. the Aurora Borealis phenomenon, causes difficulties for GPS [13] [12].

Radars and passive radar reflectors could be the key to overcome detection problems under extreme weather conditions, such as falling rain and snow. Radar systems can operate in almost all environmental conditions making them indispensable for technologies supporting autonomous vehicles, such as advanced emergency braking systems (AEBS) or adaptive cruise control (ACC). [12]

To fully utilize the radars potential for automotive applications under extreme weather conditions, we have conducted a research study that focuses on the following research questions:

1. How do different commercial passive roadside radar corner reflectors compare in terms of reflective properties for an automotive application?
2. What is the effect of snow on the performance of a passive corner radar reflector?

3. What is the influence of typical roadside infrastructure on radar signals?

The practical tests of the present study were carried out on test tracks in Rovaniemi and Muonio (Figure 2a) during the winter periods 2017/18 and 2018/19. Analogous to current prototypes of autonomous vehicles, various sensor methods, such as radar, cameras and laser scanners were applied. [12]

Three radar systems suitable for transport applications were tested in the winter period 2017/18. Hereby, the radar from Continental performed best for our future applications concerning accuracy, resolution, data output and handling. Further, different types of passive radar reflectors (commercially used and self-designed) in different form and size were tested. The results indicate that our self-designed Ø20 cm corner reflectors are a practicable, cheap and easy-to-produce alternative for our purposes compared to current products on the market. Based on these results, we developed a tubular reflector containing three Ø20 cm corner reflectors (Figure 2b, 2c). The three reflectors can be rotated against each other and positioned along the same axis in the tube to optimize the visibility. A plastic cover protects the single reflector plates from falling snow. Moreover, the effect of humans, snow and roadside infrastructure on the radar signal was investigated. The obtained results indicate that typical roadside infrastructure, such as lamp poles, are not practical as proper radar reflectors for the tested radar systems. Pedestrians did also not affect the measurements performed with our setup. [12]

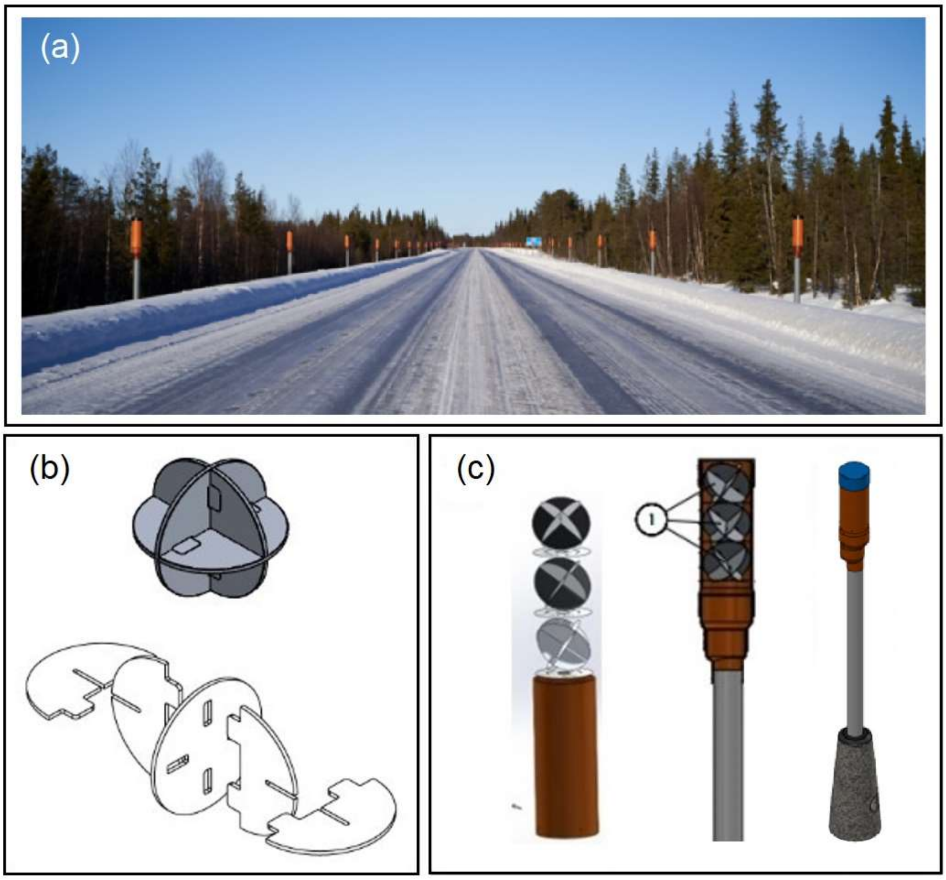

Figure 2 Self-designed reflectors. (a) Photograph of the experimental setup in the test field in Muonio. The longitudinal distance between the reflectors is 20 m respectively (in one section 40 m). (c) Tubular reflector containing three Ø20 cm corner reflectors (b). A plastic cover (brown) protects the single reflector plates from falling snow. [12]

Studying the self-designed reflector poles on a road was the focus of the experiments in the winter period 2018/19. In the first part of the experiments, the test field including 97 self-designed tubular reflector poles was monitored with our test vehicle. The test should clear up, if and how well the poles are detectable by radar at a driving speed of 80 km/h. The results show that, all 97 self-designed tubular reflector poles could be detected with a driving speed of 80 km/h. This result is particularly important because all the previous tests conducted in 2017/18 were performed with a maximum speed of 30 km/h. It was further found that reflector poles on the right side of the test vehicle send a stronger backscattered signal than corresponding poles on the left side of the car. The result can be explained by the fact that poles on the left side of the car have a larger lateral distance from the radar than the corresponding pole on the right side. The measured Radar cross-section (RCS) mean values (signal strengths) for the poles are $\sigma_{right} = (65 \pm 4{,}9)$ m² and $\sigma_{left} = (49 \pm 3{,}3)$ m². In comparison to other objects along the roadside (e.g. snow poles, signs), the detected RCS values of our self-designed reflector poles are on average two up to three times larger. The data show further smaller standard deviations for the detected RCS in the near range area compared to long distance measurements.

The second part of the tests focuses on the influence of the driving speed on the positioning and the detected signal strength of the reflector poles. The data shows that the positioning of the reflector poles is more accurate at lower vehicle driving speeds (Figure 3). Moreover, the longitudinal distances between the vehicle and the detected reflector poles affects the accuracy of the positioning. The positioning of a pole in the near range area, which means at longitudinal distances between 0 and 70 m, is on average more accurate than in the far range area. Moreover, the results show that the self-designed reflector poles are well detectable at all tested speeds in the near and far range area. At higher speeds, peak values in the RCS were no longer detected. This leads to lower detected RCS mean values.

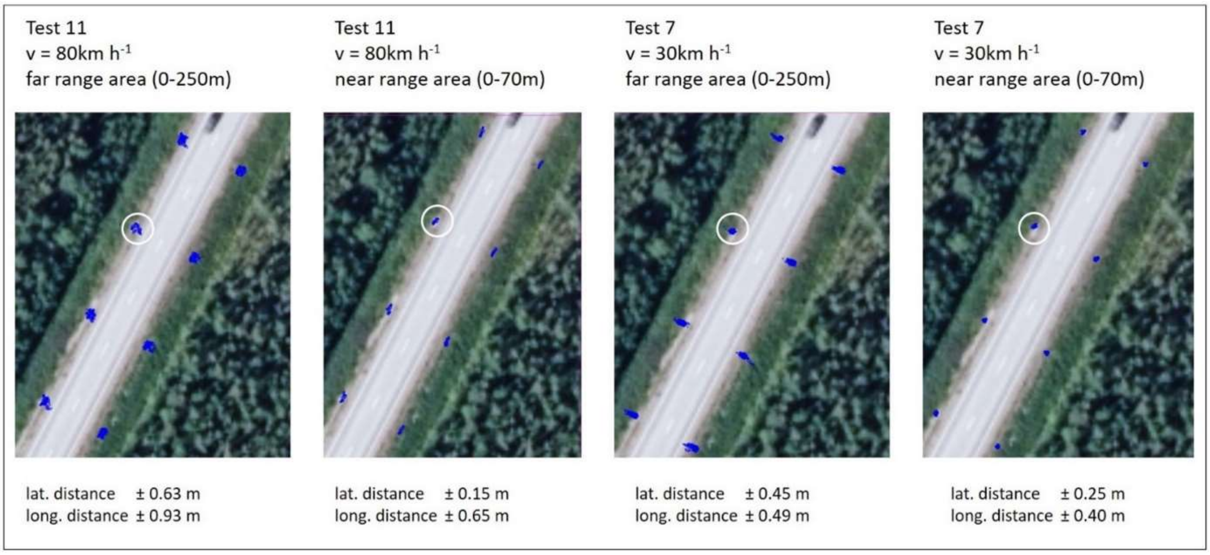

Figure 3 Influence of the driving speed on positioning the poles. The blue dots show the radar reflections produced by self-designed tubular reflector poles. The longitudinal distance between the reflector poles is 20m. [15]

The third part of the experiments shows that oncoming cars can be detected by the radar sensor from Continental up to 250 m longitudinal distance. Herby the detected signal strength of the cars is in the range of our radar reflectors. Especially close oncoming cars with trailers can block the connection between the radar and the reflector poles on the left side of the road for 2 to 3 s (v = 80 km/h). In that case, the pole on the right side is of essential importance. Oncoming cars could not block the sightline between radar and reflector poles on the right and the left side of the road simultaneously.

Finally, the influence of blowing snow on the detectability and the positioning of the self-designed reflector poles was investigated. The results indicate that blowing snow weakens the detected RCS of the reflector poles. The data further shows that the positioning of the reflector poles is less accurate if there is blowing snow between the reflector poles and the test vehicle (radar). Another result is that, under unfavourable conditions, a big truck in front of the test vehicle can obstruct the signal between the radar and those reflector poles, which are further away than the truck. The pole interval that we selected (20 m) has proven to be advantageous, because at a driving speed of 80 km/h, a safe trailing distance between two vehicles should be at least 44 m. Consequently, if the truck blocked the signal between our test vehicle and the reflector poles, at least two reflector poles per side were always within the safe trailing distance, and thus detectable. [12]

4.2. Cooperative ITS hybrid communication

Three industry companies and one research institute named as Connected and Automated Driving (CAD) coalition carried out the study of Cooperative ITS hybrid communication. The coalition's study, led by Technical Research Centre of Finland Ltd (VTT), focuses on C-ITS development and especially on V2X (vehicle-to-everything) communication together with connected and automated driving. The special point of interest in C-ITS development was to study what kind of additional requirements challenging Nordic weather conditions set for C-ITS. Two of the three field-test results, referred as testfests 1 and 2, are presented in this paper.

To answer this question, the coalition tested standardized C-ITS Day-1 services along the Aurora test road in arctic weather conditions by utilizing hybrid wireless communication solutions together with VTT's automated vehicle. The automated vehicle was used as a test vehicle for receiving C-ITS Day 1 messages in Testfest 1. In the first two Testfests, the CAD coalition tested two Day 1 messages with ETSI ITS-G5 and LTE communication technologies, precise Real-Time Kinematic (RTK) positioning and different LTE network coverages, covering both commercial and private networks.

The tested Day 1 messages were stationary vehicle (was tested also in Testfest 1) and road works warnings, which were both tested with ETSI ITS-G5 and LTE communication technologies. The tested services were implemented in a testing environment with hybrid communication capabilities. This allowed comparison between different technologies and individual networks. In the test setup, Day 1 messages were delivered to vehicles for an Android tablet, which was using cooperative mode (ETSI G5) and for an Android phone, which was using connected mode (LTE).

During the field tests, several equipment combinations were tested by changing Vehicle-to-Infrastructure (V2I) connection, positioning solution (GPS+RTK), antennas, roadside unit (RSU), on-board units (OBU), and RSU connectivity to cloud services. Simultaneously, coalition members analysed how these changes affected the results. In the first field test, tests were carried out on the parking lot of the Lapland Hotel Olos, where the Aurora Summit 2018 was held. During Testfest 2, all tests were done on the Aurora road, so that cooperative mode (ETSI G5) tests were done in Muonio town centre and the connected mode (LTE) along the Aurora road (see Figure 4).

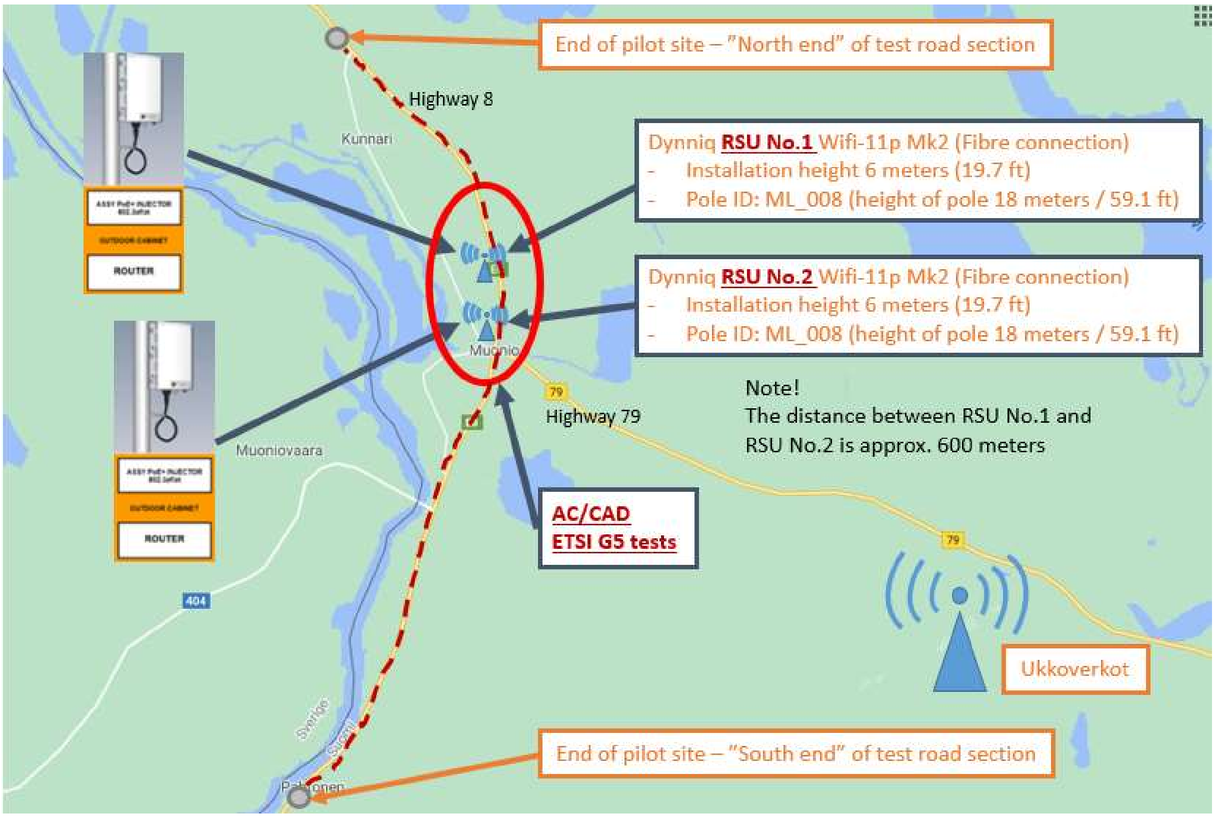

Figure 4 CAD coalition field test 2 test section. (Google Maps)

The architecture used in Testfest 2 is described below in Figure 5. In test setup, Infotripla provided a Traffic Data Analytics Cloud (TDAC) cloud service that connected the CAD coalition setup to national traffic information interfaces. It was also used to simulate road works warnings, which were delivered to test vehicles via Dynniq's CCSP (Cooperative and Connected Service Platform) cloud service and presented to the driver through Dynniq's Green flow application. The interface between Infotripla and Dynniq was a two-way communication channel, which enabled stationary vehicle message delivery also to the TDAC service.

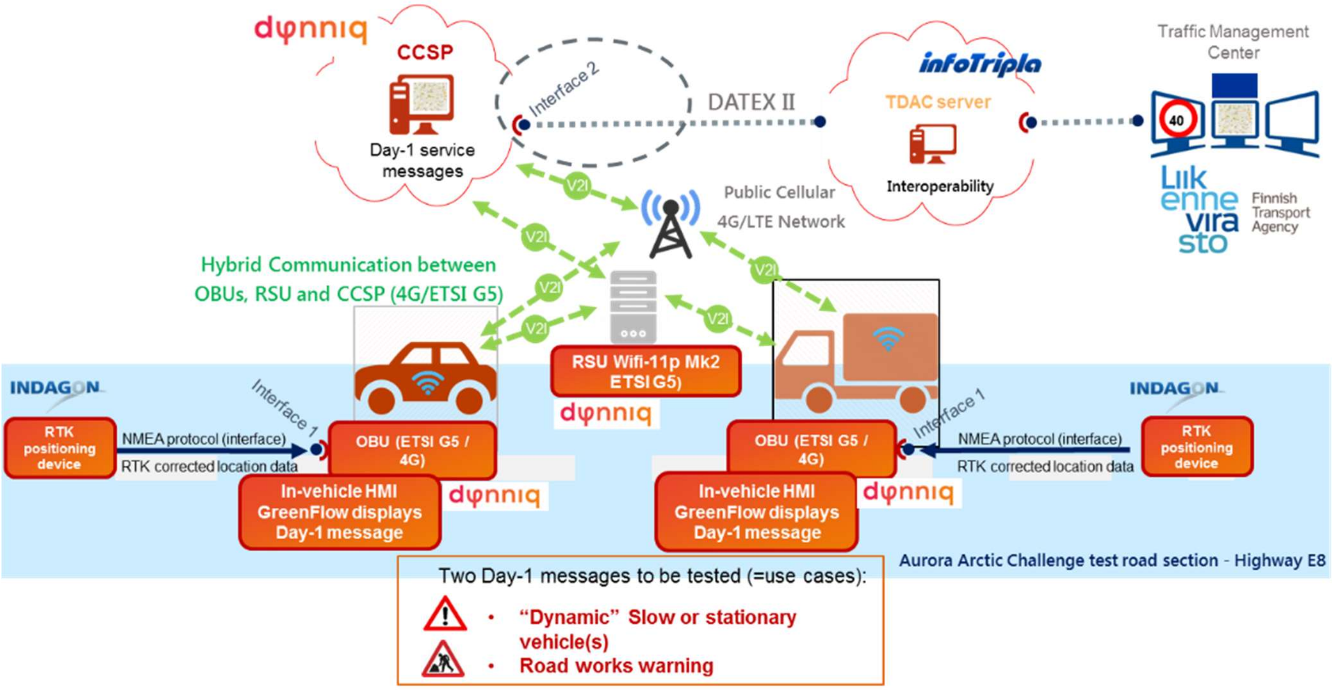

Figure 5 AC/CAD FOT system setup.

Two tests vehicles were equipped with the same devices: OBU, RTK device, Android tablet (cooperative mode), Android phone (connected mode) and PC. In addition to in-vehicle devices, AC/CAD test set-up included two RSUs and two roadside cabinets. One of the roadside cabinets also included Indagon's RTK base station, which was used for precise positioning. According to results, the RTK positioning provided centimetre level accuracy with fix to GPS and Glonass satellites (tested in Tesfest 1).

4.3. Vehicle remote control and communication infrastructure

4.3.1. Network Latency Test for Autonomous Vehicle

From a vehicle connectivity point of view, the Aurora test road provided a very good test environment for C-ITS and automation tests. One of two available commercial networks (LTE) provided good connection for the whole Aurora test road. According to measurements (done in November 2018), downlink bandwidth of the LTE connection varied between 11-45 Mbit/s and uplink bandwidth between 17-40 Mbit/s in the test area. However, these figures are based on a small number of measurements carried out during one week. Thus, it can be stated that the bandwidth was sufficient for testing of C-ITS services.

The CAD coalition C-ITS research package also included a private LTE network for Aurora tests which was provided by Indagon together with its subcontractor Ukkoverkot Ltd. The aim of this dedicated test network was to ensure network coverage in Aurora test road and to enable a possibility to adjust downlink and uplink levels in the area. However, the commercial LTE network provided better capacity for testing and therefore preferred. Qualitative comparison of the service provider's ETSI G5 and LTE technologies indicated that both have pros and cons: ETSI G5 has very good and reliable connection while LTE was not that stable in the tests. The coverage of LTE cells in the test area were more comprehensive than the ETSI G5 WIFI coverage. In addition, quantitative latency assessment between LTE (M=12.906, Mdn=12.677, SD=5.572) and ETSI G5 (M=16.388, Mdn=16.852, SD=5.563) was completed, but the results had slight inaccuracy due to data logger laptop and OBU clock synchronization calculation as well as timestamps; therefore the quantitative results should be treated with caution. More details can be found from the final report [14].

The connection between a remote control station to the autonomous vehicle and the autonomous vehicle to the base transceiver station (BTS) is analysed along the Muonio Expressway (Figure 6). The analysis examined the Internet Control Message

Protocol (ICMP) data, packet loss values, the effect of the host vehicle speed and current location (environment) towards network latency. For brevity, more details on the results for this connectivity tests analysis can be found in the final report [14].

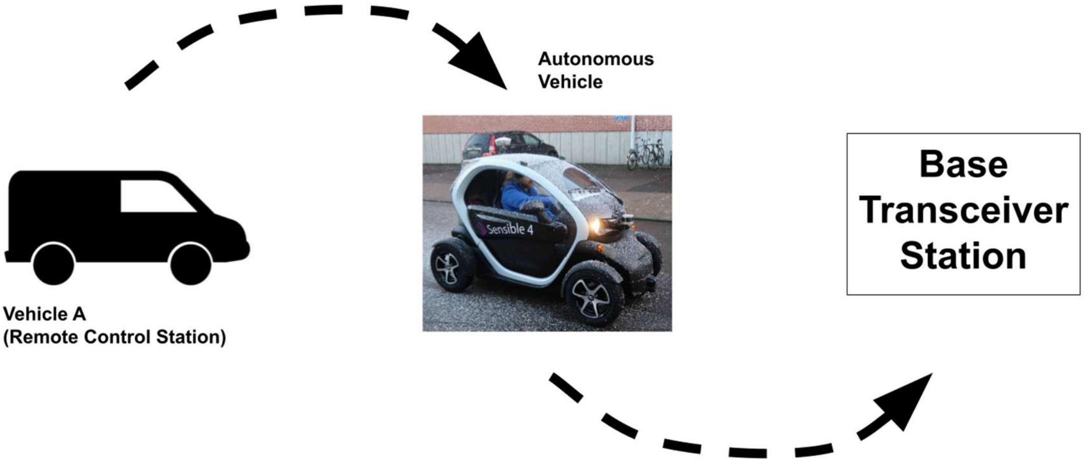

Figure 6 Schematic showing setup for network connectivity tests between Remote Control Station, Autonomous Vehicle and Base Transceiver Station along Muonio Expressway [14].

4.3.2. *Remote Control Intervention for Autonomous Vehicle in Emergency Scenario*

In certain scenarios, the independent obstacle avoidance by the host autonomous vehicle is not possible. Thus, a remote control solution is desirable to provide assistance to the collision mitigation issues. A test is done where the host vehicle initially navigates autonomously with the maximum speed of 30 km/h in a scattered environment. When a previously unknown obstacle is detected and the safety threshold is violated, the vehicle stopped. The remote operator then takes over the vehicle manoeuvre by performing a remote control obstacle avoidance over a network system. During the avoidance, the state of the vehicle is fed to the remote operator's workstation and monitored (Figure 7(left)). The remote operator guides the vehicle to the next safe point in the predetermined initial trajectory. Once the safe threshold is maintained, the autonomous navigation resumed. The results are shown in Figure 7(left) and 7(right), where the autonomous navigation is indicated by green and the remote takeover is shown in red [14].

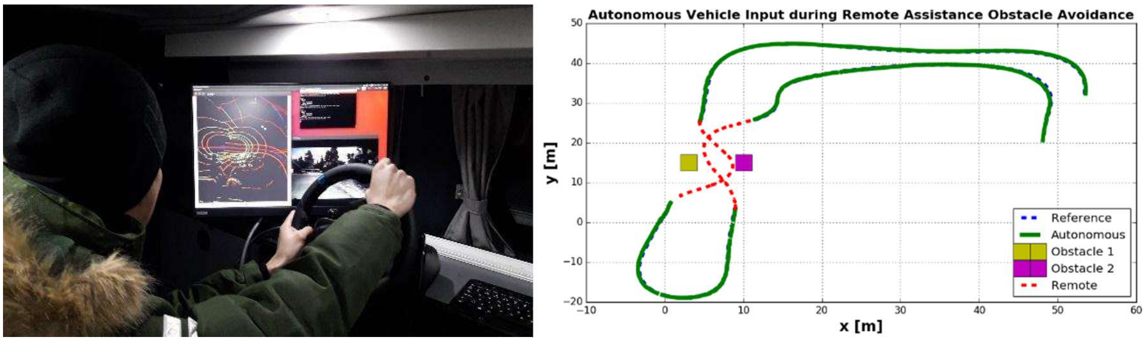

Figure 7 Remote Operator monitoring the AV navigation from the Remote Control room (left) and the remote assistance obstacle avoidance test for the AV (right) [14].

4.4. *Positioning of vehicle*

The aim of this experimental activity is to evaluate Sensible 4 Ltd.'s positioning and mapping strategy ability in providing an all-season reliable solution for the Autonomous Vehicle (AV) positioning module. Two maps are built in each non-snow and snowstorm conditions. The performance of the positioning is evaluated by having the autonomous vehicle navigating using both maps in both non-snow and snow storm conditions. The trajectories are shown in Figure 8 (left) (Google Maps snapshot), where the tests are done on the Muonio Expressway. The comparison between the vehicle actual position relative to the position information obtained from the satellite is done (Figure 8(right)). Summary of the results are shown in the Tables 1 and 2 below. For brevity, the details of the experimental setup and more discussions on the tests results for this subsection can be found in the final report [14].

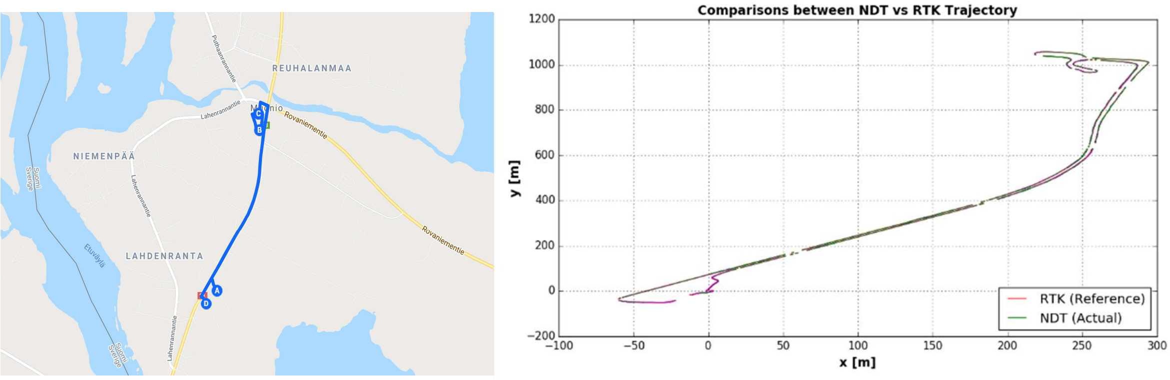

Figure 8 Trajectories used for all of the scenarios (left) and comparisons between the actual position of the vehicle (NDT) to the reference position (RTK) (right) [14].

Table 1. Analysis of the tracking error between the actual and reference positions of the vehicle in non-snow and snow storm driving using non-snow maps.

Weather Conditions	Lateral Error (m)	Average Absolute Positioning Error (m)
Non-Snow Driving	0.187	0.264
Snow Driving	0.105	0.161

Table 2. Analysis of the tracking error between the actual and reference positions of the vehicle in non-snow and snow storm driving using snow maps.

Weather Conditions	Lateral Error (m)	Average Absolute Positioning Error (m)
Non-Snow Driving	0.166	0.236
Snow Driving	0.117	0.182

5. Conclusions

The study of posts and poles in Arctic conditions contributes to the understanding of prospects and limitations of current technologies and products in the field of autonomous driving with a focus on radars and passive reflectors. The results indicated blowing snow weakening the detected signal of the reflector poles and 20 m pole interval considered advantageous in 80 km/h speeds in a traffic with possible other vehicles blocking the signal. The results give a positive prognosis for developing radar reflectors further and scale their size smaller for more practical and cost effective solution.

The C-ITS hybrid communication services of stationary vehicle and road works warning were tested in two field tests in Arctic conditions. The services performed successfully in commercial and private LTE cellular networks as well as ETSI ITS-G5. The commercial LTE cellular network offered better performance than the private LTE network and ETSI G5 V2I better stability than the commercial LTE but with lower coverage.

Based on the vehicle positioning study analysis it can be concluded that the Sensible 4 Ltd positioning solution provides reliable positioning performance to the autonomous vehicle, regardless of the environmental factors such as extreme weather as well as rural surroundings. The findings on the positioning study analysis will be extremely useful for the further work of improvement of automated vehicle's motion planning and control systems. The reliability of the positioning modules regardless of the weather conditions as shown in the results, have the potential to allow for an uninterrupted and reliable autonomous driving experience. Further works include the detailed analysis of the positioning's effects towards other autonomous driving modules such as object detection and emergency control.

The results presented in this paper need to be further analysed in collaboration with the ecosystem stakeholders to evaluate automated driving requirements in snowy and icy northern conditions as well as socio-economic aspects.

6. Acknowledgements

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