

ARCTIC CHALLENGE PROJECT'S FINAL REPORT

Road transport automation
in snowy and icy conditions



Arctic Challenge project's final report

Road transport automation in snowy and icy conditions

Research reports of the FTIA 19/2019

Cover photograph: Risto Kulmala

Online publication pdf (www.vayla.fi)

ISSN 2490-0982

ISBN 978-952-317-739-0



**Co-financed by the Connecting Europe
Facility of the European Union**

Nordic
WAY 2 

Finnish Transport Infrastructure Agency
P.O.Box 33
00521 HELSINKI, Finland
Tel. +358 (0)295 34 3000

Ilkka Kotilainen, Chris Händel, Umar Zakir Abdul Hamid, Lasse Nykänen, Harri Santamala, Anna Schirokoff, Matti Autioniemi, Risto Öörni and Niklas Fieandt: Arctic Challenge project's final report – Road transport automation in snowy and icy conditions. Finnish Transport Infrastructure Agency. Helsinki 2019. Research reports of the FTIA 19/2019. 88 pages. ISSN 2490-0982, ISBN 978-952-317-739-0.

Keywords: road transport automation, posts and poles, Cooperative ITS (C-ITS), vehicle positioning, vehicle remote control

Abstract

The development of highly automated vehicles enables safer, more efficient and environmentally friendly road transport in the future. In order for automated vehicles to reach their full potential, year-round operation in extreme weather conditions is required.

The aim of the Arctic Challenge project was to study automated driving in snowy and icy northern conditions. This Finnish public road authorities and EU CEF-funded project included three industry coalitions that were selected in a public procurement process to study four research questions in Arctic conditions related to posts and poles for guidance and positioning, Cooperative Intelligent Transport Systems (C-ITS), communication infrastructure and remote driving, as well as vehicle positioning.

The Lapland University of Applied Sciences and Roadscanners study of posts and poles in Arctic conditions contributed to the understanding of the 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 that shifting snow weakens the detected signal of the reflector poles and the 20 m pole intervals are considered advantageous at 80 km/h speeds in traffic with other vehicles possibly blocking the signal. The results give a positive prognosis for developing radar reflectors further and making them smaller in size for more practical and cost effective applications.

The VTT Technical Research Centre of Finland, Dynniq, Infotripla and Indagon consortium focused on Cooperative ITS (C-ITS) services in arctic conditions. The results indicate that the hybrid communication solution of ITS-G5 and LTE radio communication technologies used for the transmission of four Day 1 messages of stationary vehicle, animal on the road, slippery road and roadworks warnings, are functional under arctic conditions. Exchange of C-ITS messages between several operators is a prerequisite for the implementation of an efficient information and warning service with cross-border interoperability. The solution for delivery of Day-1 messages based on ETSI ITS-G5 was found to be more mature at the time when tests were carried out, but it provides more limited geographical coverage compared to cost of implementation than the solution based on commercial LTE networks.

The Sensible 4 consortium focused on three research questions: How active poles could be utilised for guiding automated vehicles in difficult conditions, the remote control of automated vehicles in harsh conditions and the loss of road lane markings and GNSS, and how can automated vehicles localise themselves in such situations. As a result of the project it has been shown that UWB technology can offer a positioning accuracy of a few centimetres, and remote control can be a viable method for borderline cases if minimum network requirements are met. Lidar-based positioning can be a primary positioning method, even in Arctic conditions. The solution used by Sensible 4, combining multiple sensors as well as non-linear algorithms with satellite information, yield a reliable positioning performance of an automated vehicle with a maximum average error of 0.264 m and lateral error of 0.187 m in all conditions using a single HD map.

The development of autonomous driving systems should be continued to better ensure performance in harsh weather conditions. This requires the development of both hardware and software, and collaboration between industry and the public sector.

Ilkka Kotilainen, Chris Händel, Umar Zakir Abdul Hamid, Lasse Nykänen, Harri Santamala, Anna Schirokoff, Matti Autioniemi, Risto Öörni ja Niklas Fieandt: Arctic Challenge – tutkimushankkeen loppuraportti - Tieliikenteen automaatio lumisissa ja jäisissä olosuhteissa. Väylävirasto. Helsinki 2019. Väyläviraston tutkimuksia 19/2019. 88 sivua. ISSN 2490-0982, ISBN 978-952-317-739-0.

Avainsanat: tieliikenne, automaatio, reunapaalut, viestintä, paikannus, etäohjaus

Tiivistelmä

Pitkälle automatisoitujen ajoneuvojen kehittäminen mahdollistaa tulevaisuudessa turvallisemman, tehokkaamman ja ympäristöystävällisemmän tieliikenteen. Jotta automatisoidut ajoneuvot saavuttaisivat täyden potentiaalinsa, niiden on kyettävä toimimaan ympäri vuoden äärimmäisissä sääolosuhteissa.

Arctic Challenge hankkeen tavoitteena oli tutkia automatisoitua ajamista pohjoisen lumisissa ja jäisissä olosuhteissa. Suomen liikenneviranomaisten ja EU:n Verkkojen Eurooppa välineen rahoittamaan hankkeeseen osallistui kolme yritysten yhteenliittymää, jotka valittiin julkisessa hankintamenettelyssä tutkimaan seuraavaa neljää tutkimuskysymystä arktisissa olosuhteissa: ohjausta ja paikannusta varten käytettävät paalut ja pylvää, yhteistoiminnalliset älyliikennejärjestelmät (C-ITS-järjestelmät), tietoliikenneinfrastruktuuri ja etäohjaus sekä ajoneuvon paikannus.

Lapin ammattikorkeakoulun ja Roadscannersin tutkimus paaluista ja pylväistä arktisissa olosuhteissa lisäsi ymmärrystä nykyisten teknologioiden ja tuotteiden tulevaisuuden näkymistä ja rajoituksista autonomisen ajamisen alalla. Tutkimuksessa keskityttiin tutkiin ja passiivisiin heijastimiin. Tulokset osoittivat, että lumipyry heikensi heijastinpylväiden signaalin havaitsemista ja että pylväiden sijoittamista 20 metrin välein pidetään suotavana 80 kilometrin tuntinopeuksissa liikenteessä, jossa mahdolliset muut ajoneuvot voivat olla signaalin tiellä. Tulosten ennuste oli myönteinen tutkaheijastinten kehittämiseksi edelleen ja niiden koon pienentämiseksi käytännöllisemmän ja kustannus- tehokkaamman ratkaisun löytämiseksi.

Teknologian tutkimuskeskus VTT:n, Dynniqin, Indagonin ja Infotriplan yhteenliittymä keskittyi yhteistoiminnallisten älyliikennejärjestelmien (C-ITS) palveluihin arktisissa olosuhteissa. Tulokset osoittavat, että pysähtyneestä ajoneuvosta, tiellä olevasta eläimestä, liukkaasta tienpinnasta ja tietöistä varoittavien Day-1-viestien välittämiseen käytettävien ITS-G5- ja LTE-teknologioiden hybridiratkaisu on toimiva arktisissa olosuhteissa. C-ITS-viestien välittyminen useiden toimijoiden välillä on edellytys tehokkaan, kansainvälisenkin yhteentoimivan järjestelmän toteuttamiseksi. ETSI:n ITS-G5-teknologia tarjoaa parempaa vakautta mutta pienempää kattavuutta kuin kaupallinen LTE-teknologia.

Sensible 4 -yhteenliittymä keskittyi seuraaviin kolmeen tutkimuskysymykseen: Miten aktiivisia pylväitä voitaisiin käyttää automatisoitujen ajoneuvojen ohjaamisessa vaikeissa olosuhteissa, automatisoitujen ajoneuvojen etäohjaus ankarissa olosuhteissa ja kaistamerkintöjen ja GNSS:n häviäminen ja miten automatisoitu ajoneuvo voi paikantaa itsensä tällaisissa tilanteissa. Hankkeessa osoitettiin, että UWB-teknologia voi mahdollistaa muutaman senttimetrin paikannustarkkuuden ja että etäohjaus voi olla toteuttamiskelpoinen vaihtoehto rajatapauksissa, jos tietoverkon vähimmäisvaatimukset täyttyvät. Valotutkaan (LiDAR) perustuva paikannus voi toimia ensisijaisena paikannusmenetelmänä jopa arktisissa olosuhteissa. Sensible 4:n käyttämä ratkaisu, johon oli yhdistetty useita antureita ja ei-lineaarinen algoritmi satelliittitiedoilla, tuotti luotettavan automatisoidun ajoneuvon paikannustuloksen, jossa keskimääräinen virhe oli enintään 0,264 metriä ja lateraalinen virhe 0,187 metriä kaikissa olosuhteissa käytettäessä yksittäistä HD-karttaa.

Autonomisten järjestelmien kehittämistä olisi jatkettava, jotta voidaan varmistaa paremmat tulokset myös ankarissa sääolosuhteissa. Tämä edellyttää sekä laitteistojen että ohjelmistojen kehittämistä ja yritysten ja julkisen sektorin välistä yhteistyötä.

Ilkka Kotilainen, Chris Händel, Umar Zakir Abdul Hamid, Lasse Nykänen, Harri Santamala, Anna Schirokoff, Matti Autioniemi, Risto Öörni och Niklas Fieandt: Slutrapport för forskningsprojektet Arctic Challenge – Automatisering av vägtrafik i snöiga och isiga förhållanden. Trafikledsverket. Helsingfors 2019. Trafikledsverkets undersökningar 19/2019. 104 sidor. ISSN 2490-0982, ISBN 978-952-317-739-0.

Sammanfattning

Utveckling av fordon som i hög grad är automatiserade möjliggör mer säkra, effektiva och miljövänliga vägtransporter i framtiden. För att de automatiska fordonen ska nå sin fullständiga potential, krävs att de kan användas året runt, under extrema väderförhållanden.

Syftet med projektet Arctic Challenge var att studera automatiserad körning i nordiska väderförhållanden med snö och is. Finska allmänna vägmyndigheter och EU-finansierade projekt inom ramen för Fonden för ett sammanlänkat Europa inkluderade tre branschförbund som valdes ut genom allmän upphandling för att studera fyra forskningsfrågor i arktiska väderförhållanden: stolpar och pålar för vägledning och positionering, kooperativa intelligenta transportsystem (C-ITS), kommunikationsinfrastruktur och fjärrstyrning samt positionering av fordon.

En studie från Lapplands universitet för tillämpad vetenskap och Roadscanners av stolpar och pålar i arktiska förhållanden bidrog till förståelsen av prospekteringar och begränsningar av nuvarande tekniker och produkter inom självkörande fordon med fokus på radar och passiva reflektorer. Resultaten visade att snöyra försvagade den detekterade signalen från de reflekterande stolparna och 20 meters intervall mellan stolparna ansågs vara fördelaktigt vid hastigheter på 80 km/timmen i trafik med eventuella andra fordon som skymmer signalen. Resultaten ger en positiv prognos för att utveckla radarreflektorer vidare och göra deras storlek mindre, för en mer praktisk och kostnadseffektiv lösning.

Sammanlutningen av Teknologiska forskningscentralen VTT, Dynniq, Indagon och Infotripla fokuserade på tjänster för kooperativa intelligenta transportsystem (C-ITS) i arktiska förhållanden. Resultaten visar att en hybridlösning som kombinerar ITS-G5- och LTE-teknologier, vilka används för att förmedla Day-1-meddelanden som varnar för fordon som stannat på vägen, djur som befinner sig på vägen, halka och vägarbeten, fungerar i arktiska förhållanden. Förmedling av C-ITS-meddelanden mellan flera operatörer är en förutsättning för genomförande av ett effektivt, även internationellt kompatibelt system. ETSI:s ITS-G5-teknologi erbjuder bättre stabilitet men mindre omfattande täckning än den kommersiella LTE-teknologin.

Sensible 4 consortium fokuserar på tre forskningsfrågor: Hur aktiva pålar kan användas för att vägleda automatiserade fordon i svåra förhållanden, fjärrkontroll av automatiserade fordon i svåra förhållanden och förlust av körfältsmarkeringar och GNSS, och hur de automatiserade fordonen kan lokaliserars i sådana situationer. Till följd av projektet har det visat sig att UWB-teknik kan erbjuda positionsbestämning på några centimeter, fjärrkontroll kan vara en möjlig metod för gränsfall om nätverkets minimikrav uppfylls. Ledarbaserad positionering kan vara den primära positionsmetoden även i arktiska förhållanden. Den som används av Sensible 4, genom att kombinera flera sensorer liksom icke-linjär algoritm med satellitinformationen ger en tillförlitlig positionsprestanda med ett automatiserat fordon med maximalt genomsnittligt fel på 0,264 m och sidofel på 0,187 m i alla väderförhållanden, med användning av en enda högdefinierad karta.

Utvecklingen av autonoma system bör fortsätta för att bättre säkerställa prestandan, även i svåra väderförhållanden. Detta kräver utveckling av både maskinvara och programvara och samarbete mellan näringslivet och den offentliga sektorn.

Foreword

This report presents a summary of the studies conducted and the results obtained in the Arctic Challenge research project.

The project was carried out by three different research groups led by Lapland University of Applied Sciences, Technical Research Centre of Finland (VTT), and Sensible 4 Ltd under the guidance of Finnish Transport and Communications Agency Traficom. Roadscanners Ltd performed studies in cooperation with Lapland University of Applied Sciences. The consortium led by VTT included Dynniq Finland Ltd, Indagon Ltd and Infotripla Ltd as well as the subcontractor Ukkoverkot Ltd. The Sensible 4 consortium consisted of Metropolia University of Applied Sciences, Finnish Meteorological Institute, Sharpeye Systems Ltd, MHR Consulting, F-Secure Ltd and its subsidiaries, Solidpotato Ltd and Nodeon Ltd.

During the project, the primary representatives of authorities and consortia participating in steering group work were Ilkka Kotilainen (Traficom and Finnish Transport Agency, Niklas Fieandt (Finnish Transport Infrastructure Agency FTIA), Anna Schirokoff (Traficom), Risto Kulmala (Finnish Transport Agency), Eetu Pilli-Sihvola (Traficom), Heikki Konttaniemi (Lapland University of Applied Sciences), Matti Autioniemi (Lapland University of Applied Sciences), Timo Saarenpää (Roadscanners), Chris Händel (Roadscanners), Lasse Nykänen (VTT and Vediafi), Risto Öörni (VTT) and Harri Santamala (Sensible 4). Many intelligent transport and automation experts working in different positions at companies and in the transport infrastructure sector also contributed to the work.

The Arctic Challenge research project was part of the Aurora project to promote intelligent transport and the digitalisation and automation of transport infrastructure maintenance, which the Finnish Transport Agency (Finnish Transport Infrastructure Agency as of the 1st of January 2019) implemented in 2016–2018 as part of the transport infrastructure project for Highway 21 Aurora. Trial and test activities in the Arctic Challenge project continued in 2019 in the form of basic transport infrastructure research and development projects conducted by the Finnish Transport and Communications Agency. (Aurora 2019)

The Arctic Challenge project also received funding from the Connecting Europe Facility (CEF) programme as part of the NordicWay 2 project.

Helsinki, November 2019

Finnish Transport Infrastructure Agency
Road data services

Content

1	INTRODUCTION	8
1.1	Background and objectives	8
1.2	Procurement	9
1.3	Testing plan and methods.....	9
1.3	Ethical perspectives	11
1.4	Structure of the report	11
2	RESULTS	12
2.1	Posts and poles.....	12
2.1.1	Active poles guidance	12
2.1.2	Passive posts and poles with reflectors	16
2.1.3	Results and Discussion.....	22
2.2	Cooperative ITS	36
2.2.1	Background.....	36
2.2.2	Objectives.....	36
2.2.3	Methods.....	37
2.2.4	Test results.....	38
2.2.5	Evaluation of results	61
2.3	Vehicle remote control and communication infrastructure	62
2.3.1	4G/LTE Network LTE	63
2.3.2	5G test network measurements for reference.....	65
2.3.3	Remote control obstacle avoidance test.....	66
2.4	Vehicle positioning.....	68
2.4.1	GNSS positioning	68
2.4.2	HD maps (SolidPotato approach).....	69
2.4.3	Lidar based positioning (Sensible 4 approach)	73
3	CONCLUSIONS	76
3.1	Posts and poles.....	76
3.1.1	Active poles guidance	76
3.1.2	Passive posts and poles with reflectors	77
3.2	Cooperative Intelligent Transport Systems (C-ITS)	79
3.3	Remote control and communication infrastructure.....	82
3.4	Vehicle positioning.....	83
4	DISCUSSION	85
	SOURCES.....	87

1 Introduction

1.1 Background and objectives

The development of automated driving enables safer, more efficient and environmentally friendly road transport in the future. Highly automated vehicles could become the most important transformation in the automobile industry in the current century. In most cases, the high level of automation is largely based on positioning systems, such as GPS and the use of fast networks like 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. As a result, the accurate and reliable detection of vessels and other objects such as physical land infrastructure is a challenging task for scientists and engineers.

Most 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. Radars and passive radar reflectors could be key to overcoming 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). On snow-covered roads, lane markings are not visible either. Drifting and blowing snow practically block the vision of any camera system, and causes major difficulties for LiDAR systems as well. Further, the availability of satellite positioning is more limited in Arctic areas and magnetic storms and other conditions, such as the Aurora Borealis phenomenon, cause difficulties for GPS

The objective of the Arctic Challenge project was to study automation and intelligent infrastructure solutions for road transport and the functionality of these solutions in Arctic conditions. This was done using the following four research questions:

1. Posts and poles for guidance and positioning: What kind of landmarks, such as roadside and reflector posts or snow poles and plot access markers, are required for automated driving? Where should they be placed? What should they be like?
2. Cooperative traffic information: What kind of C-ITS Day 1 hybrid services to improve traffic flow and safety should be implemented in the Aurora Borealis corridor located in western Lapland and Norway? How should they be implemented and what is their technical functionality level?
3. Remote control and wireless data transfer: How do remote vehicle control and monitoring function via hybrid communication in good and poor weather conditions? What minimum requirements must the communications network meet in order to enable remote control of automated cars?
4. Location data and positioning: How and to what accuracy can a vehicle's position be specified for the needs of automated driving at northern latitudes under conditions in which the shoulder markings or the road are not visible? How do different methods function in special locations and situations, such as shadow areas and reflections?

The research questions set for the project and their principles are presented in more detail in the "Road transport automation road map and action plan 2016–2020" publication (Finnish Transport Agency 2016).

1.2 Procurement

Specification of the research questions for the Arctic Challenge project was based on the Road transport automation road map and action plan 2016–2020 (Finnish Transport Agency 2016). From that report, the areas of transport infrastructure, data communications, location data and positioning, impact assessment, and data were selected for more detailed review.

The next step was a market survey, the first phase of which involved publishing a public request for information in the HILMA channel. The main topics of this request were also translated into English and distributed to European stakeholders. The objective of the request for information was to survey the views of market operators concerning the research questions and identify any questions they might have for the authorities. The second phase involved arranging an open dialogue event for market operators that showed interest in the request for information. The dialogue involved discussion of the research entities and presented answers to the questions posed by the operators.

Based on the market survey, a decision was made to invite tenders concerning seven research questions. Tenders were received from three consortia, each of which presented its solutions to the research questions.

In addition to tender evaluations performed by the client authorities, a negotiation event was held where the client authorities and the consortia operators discussed implementation of the research entity. The negotiations held on the basis of the invitations to tender led to selection of the four most important research questions (section 1.1 Background and objectives), regarding which the client authorities signed an agreement with the three consortia. Research question 1 was the responsibility of Lapland University of Applied Sciences and Roadscanners in cooperation with the Sensible 4 consortium. The VTT consortium handled research question 2. The Sensible 4 and VTT consortia were responsible for research question 3, and the Sensible 4 consortium for research question 4. The composition of the consortia are described in the foreword.

1.3 Testing plan and methods

In cooperation with the client authorities, the consortia compiled a detailed work and testing plan that included agreement about the research responsibilities of the operators and three joint test weeks to be arranged on the Aurora E8 Intelligent Road (Traffic Management Finland Group 2019).

The test weeks were prepared and implemented in cooperation between the client authorities and the consortia. Each consortium was responsible for coordinating the planning and implementation of one test week.

Testing was performed with two automated vehicles and several instrumented vehicles equipped with, for example, radar sensors and positioning devices

(Figures 1 and 2). The objectives were the starting point for setting detailed parameters for the activities and the Key Performance Indicators used to assess the activities. This made it possible to evaluate achievement of the objectives using reliable quantitative and qualitative indicators.



Figure 1. Sensible 4's "Ava" test vehicle



Figure 2. "Martti" automated vehicle that was used in the C-ITS trials.

1.4 Ethical perspectives

Prior to each test week, the corporate operator responsible for that session informed the authorities and contractors in the region about the actions via e-mail whenever the work included infrastructure installations or some other test that could interfere with traffic flow, such as driving with an automated car. The Northern Finland Traffic Management Centre and Pirkanmaa Centre for Economic Development, Transport and the Environment also communicated about the testing. In addition, press release was published and a presentation and discussion event held for local residents.

The consortia reported three main factors that were considered to influence road safety when testing automated vehicles: cars and lorries overtaking an automated vehicle, the slow speed of an automated vehicle or its difference in speed in relation to other traffic, and poor weather conditions.

The following actions were implemented to improve road safety. If necessary, drivers were warned about the presence of an automated car on the road using a changing traffic sign (Figure 3), and the speed limit was lowered from 100 km/h to 80 km/h. One of the consortia used a safety car travelling behind the automated vehicle to warn other drivers. All representatives of the companies participating in the test week were required to have valid Road Safety 1 training and each project managers needed to have Road Safety 2 training (Finnish Transport Infrastructure Agency 2019). The test period also revealed the importance of shoulders and bus stops as a way to provide space for other traffic or to stop the vehicle on the side of the road due to possible technical problems.



Figure 3. A changing traffic sign (left) and safety car (right) warning drivers about an automated vehicle during the test period. (images: Risto Kulmala on the left, Sensible 4 on the right)

1.5 Structure of the report

This research report was compiled by the consortia and experts from the agencies that participated in the research work. The results from each consortium are presented in separate sections. The results obtained by Lapland University of Applied Sciences and Roadscanners and by Sensible 4 that are presented in Section 2 Results represent a partial summary of the results published by the consortia. If the results have been published earlier, for example, as a scientific paper, this paper is referenced in the text. In such cases, the sources used have also been referenced at the end of the section. The results of the VTT consortium have not been published elsewhere.

2 Results

2.1 Posts and poles

The major problem with automated driving in harsh road conditions is related to the need for exact positioning on the road. Snowy and icy conditions usually cover roads entirely, preventing the use of traditional technologies that utilise road markings, for example. An idea arising from earlier studies on improving positioning needs was to focus on passive and active intelligent road posts and poles. However, no practical solutions were available and had to be developed and tested in the Arctic Challenge project.

2.1.1 Active poles guidance

In this part of the work, an experimental field test set-up utilising Ultra-Wide-Band (UWB) positioning technology was created. UWB beacons were developed for the tests by SharpEye Systems Ltd. UWB beacons were installed along the vt21 road and utilised for accurate positioning. The overall accuracy tests consisted of 11 separate test sessions carried out over several days. Each session lasted a few minutes (between 1 and 5 minutes each) where a stationary car unit measured distances to several different beacons along the test road. For each session the number of beacons within radio distance of the car unit varied somewhat. The specific individual beacons that were used also varied during the tests so that overall 21 different beacon units were included in the tests. This means that the tests were representative of any hardware unit variations.

The set-up was tested with different parameters such as speed, distance to pole and weather. The positioning accuracy was analysed from the results. Recommendations for deployment parameters for UWB system are discussed in the conclusions from the research. Most of the field tests were performed with the Sensible 4 test vehicle "Juto".

Table 1. KPI's for UWB tests.

KPI	Target Value
Accuracy	under 50mm
Range	over 100m
Weather effect	none

The total number of individual successful distance measurements in the 120 measurement sessions was over 100 000. A summary of the above test quantity parameters is given in the following table.

Table 2. Summary of test parameters.

Test sessions	11
Individual beacons	21
Beacon tests total	120
Individual measurements	102082

Double-sided two-way ranging was used in these tests for time-of-flight distance measurement.

Active poles guidance results

The positioning of UWB poles was compared to known exact positioning.

The measurement error standard deviation over the individual 102,082 distance measurements was 27 mm when the vehicle was not moving. Ideally, the measurement result would be the same for every measurement, but electromagnetic noise and various environmental variations will cause small deviations to the measurement results. This report quantifies those deviations.

It was decided that the relevant accuracy measure is the error standard deviation with several repeated consecutive measurements. The result shows that the "best" test (Test 9) had an error of 20 mm while the "worst" test (Test 1) had an error of 36 mm. When the error is analysed against data speed then the error is 22 mm for 6.8 Mbps, while it is 33 mm for 110 kbps data rates. Note that these results still aggregate all different beacons and the different test sessions together.

The error deviation per beacon as measured across all tests varies between 16 and 33 mm. The variations are due to at least the physical positions of the beacons with respect to the terrain, the hardware variations in the beacon units, as well as the directional alignment between the car unit and the beacon antennas.

A specific property of this UWB time-of-flight measurement technique is that the measurement error is largely independent of the measured distance. This is well illustrated in the following graph where all the 120 measurement sets have been mapped with distance vs. error standard deviation. Each point in the graph represents an error in a measurement towards a specific beacon at a specific distance. The red trend line represents the best linear fit to the data showing essentially flat behaviour of the error deviation with respect to distance.

Finally, the error distribution can reasonably be assumed to be normal. This is well supported by these tests as shown by the following graph. The 102,082 measurements across the 120 measurement sets were "normalised" to standard deviation 1 and then combined to a single distribution. The resulting histogram is shown in the following graph (Figure 4).

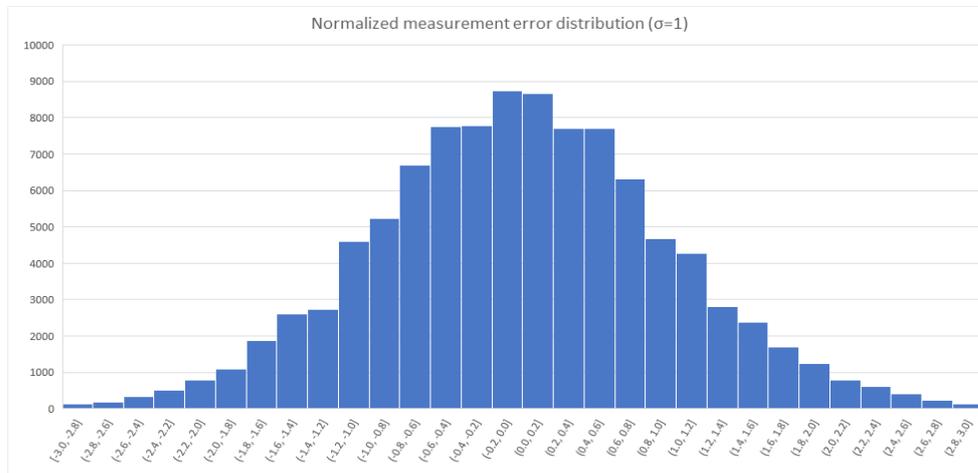


Figure 4. Histogram of the measurements.

A specific test day was arranged to measure UWB accuracy against the reference positioning system. Test data gathering was carried out at Kiikala Airport. The test set-up of 13 UWB beacons was installed in a zigzag format on both sides of the runway. The distance between beacons was 40 metres each side. The development platform used for data gathering was the Juto vehicle.

The data collection and analysis in this chapter come from Tatu Sara-Aho's Diploma thesis (Sara-Aho, 2018). His diploma thesis focus is to study different UWB positioning algorithms. He compared the performance of the algorithms at different vehicle speeds. Algorithms are based on the particle filter and the extended Kalman filter technologies. The thesis includes a statistical analysis of positioning accuracy and heading accuracy. In this chapter only the main findings are summarised.

During the test, four different test scenarios were studied:

- 1) driving one lap around the area at below 10km/h,
- 2) driving one lap around the area at 35km/h,
- 3) driving one lap around the area at 55 km/h,
- 4) driving multiple laps around the area at medium speed, varying between straight and winding tracks.

Based on the testing results at a speed 10km/h, there are no visible differences in terms of accuracy. Standard deviation on accuracy is 9.5cm on both positioning algorithms (particle filter and Kalman filter). This result meets the requirements set on autonomous vehicle localisation accuracy (Sara-Aho, 2018).

The standard deviation at 35km/h is 19.6 cm with the Kalman filter and 21.0 cm with the particle filter. The difference is very marginal between filter technologies, and coming to a conclusion about which one is better is not possible. This result seems to be in the ballpark of when accuracy can be a problem for autonomous vehicle navigation.

At 55 km/h the Kalman filter's standard deviation of positioning is 27 cm. The particle filter's standard deviation is 1.01 metres, which is obviously too much for autonomous vehicle navigation. The particle filter performed well on the first trial, but there was a major slip during the second trial. There is a difference of 2–3 metres in an X-axis direction compared to the reference positioning system. The graphs indicate that the positioning error is higher at the car's turning points, but performance is more stable on straight lines. One reason could be that at the turning points UWB beacons are located on only one side, which is challenging for locating a car on the X-axis direction. It can be assumed that UWB beacon positions are one source of an increase in positioning error at turning points. If a vehicle makes a U-turn in the middle of a UWB network, the error should be smaller. Another improvement to UWB networks could be to increase the measurement frequency from 20 Hz. Speeding up the measurement frequency produces more data points per second to calculate the positioning of car.

UWB Range

A tracker on a car receives the first beacon's UWB signal from a distance of 350 metres. The car drives through the network until the UWB signal is lost. Then the driver makes a U-turn and enters the UWB network again from the opposite direction. When the UWB signal is lost for a second time, the logging of data is stopped. In the graph below, this procedure is seen as two individual plots in a V-shape. Each beacon has its own hex number code and colour coding. The Y-axis represents distance and the X-axis the timestamp.

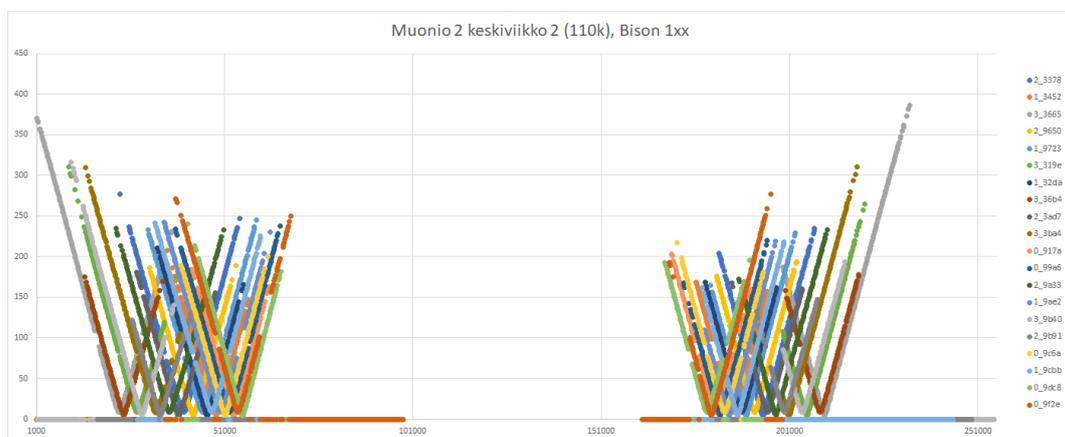


Figure 5. One test drive with 110k data speed used on this test.

UWB communication range depends on how good the line of sight is between the car tracker and the individual beacon. Obstacles like cars, snowbanks or bus stops can block a UWB signal, cause wrong distance measurements or shorten range. In testing there was mostly clear line of sight.

Three different UWB data speeds were tested: 110k, 850k and 6.8M. One major finding was that a 6.8 Mbit/s range is significantly lower than 110k and 850k. The range was slightly under 100 metres. 110k and 850k were on a similar level from a range point of view.

An important factor that effects the connection range is TX power levels. A testing system was designed for research usage. In actual production, power levels need to be lowered. Lower power levels directly reduce the range of the UWB system. The estimation is that in production quality UWB might achieve a range of 200 metres with 110k and 850k data speeds.

Weather effects of UWB

During the testing in Muonio, extreme weather conditions were not encountered. Temperatures varied between +0° and -16° Celsius. On some days it snowed lightly while a few other days recorded relatively high humidity, and a thin layer of ice and snow formed on top of the beacon.

Table 3. Weather in Muonio on successful testing days.

Temperature	Snowing or not
-10° Celsius	Snowing lightly
-5° Celsius	Snowing lightly
+0° Celsius	Snowing, some snow and ice formation on beacon mechanics
-2° Celsius	Not snowing
-5° Celsius	Not snowing, high humidity
-11° Celsius	Not snowing
-16° Celsius	Snowing lightly
-13° Celsius	Snowing lightly

Based on the performed tests and data, we cannot form any conclusion that weather like temperature, humidity or snow has any effects on UWB measurements. This problem should be studied further in future tests or in a laboratory environment.

2.1.2 Passive posts and poles with reflectors

Road traffic is becoming more and more digital, automated and connected [1]. Some automated cars, such as the self-driving vehicle from Google, are already operating on public roads or are in the development and testing phase [2]. The automation of these vehicles is mostly based on sensors (e.g. radars, Lidars, GPS and cameras) detecting their surroundings and environment [3, 4]. (Händel C, Saarenpää T & Autioniemi M, 2019)

Despite the global importance of automated vehicles to the future of road transport, most of the field tests are carried out under ice- and snow-free weather conditions. Harsh winter conditions in particular cause numerous challenges for automated cars and their sensors. Snowstorms, for example, can blind cameras and magnetic storms can cause major difficulties for GPS systems [5]. Furthermore, obscured lane markings are a problem for automated vehicles, especially in the northern countries. (Händel C, Saarenpää T & Autioniemi M, 2019)

Radar systems can operate in these harsh weather conditions. The emitted radar waves can penetrate rain, dust, fog and snow, making those systems indispensable for current technologies supporting automated vehicles (e.g. ACC). Strong reflecting objects along the roadside could support the navigation of vehicles using high frequency (76-81 GHz) radars. [6] (Händel C, Saarenpää T & Autioniemi M, 2019)

2.1.2.1 Background and Methods

Test Field, Outer Conditions and Test Preparation

All tests were performed on test tracks to provide comparable experimental conditions between different tests. One is located near the airport at Rovaniemi and one in Muonio on a ≈ 10 km instrumented road section (Aurora Intelligent Road) on Finnish national road 21, which is part of the European route E8. The first mentioned test field is 25 m wide and 165 m long, (Figure 6a and 6b). For the tests in Muonio, a ≈ 1.5 km long road section was selected from the Aurora Intelligent Road and prepared with 100 reflector mounting poles, on top of which the actual reflector tubes were installed prior to the test period (Figure 6c). The section includes a total of 189 holders for reflector mounting poles (20 m distance, respectively) on the left and right side of the road (Figure 7a and 7b). The distance between reflector pole holders and the road was always 3 m during the tests. Holders with a smaller distance from the road were not chosen in order to avoid problems with winter road maintenance. All experiments were performed under winter conditions (Figure 7c). The radar enclosure height was 60 cm above the ground in both test tracks. The test period was between 4 and 8 March 2019 and before that the reflectors were assembled and installed inside the reflector tubes. The road safety planning and the necessary road safety announcements were made in cooperation with the authorities before the test period. On the first test day, the reflector tubes were mounted on top of the reflector poles and the necessary road safety measures were taken. (Händel C, Saarenpää T & Autioniemi M, 2019)

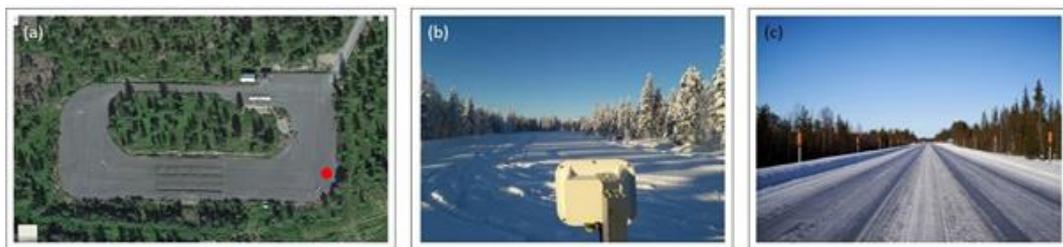


Figure 6. Test fields in Rovaniemi and Muonio. (a) Photograph of the test field in Rovaniemi ($66^{\circ}32'52''N$ $25^{\circ}48'36''E$) [7]. The red dot shows the position of the radars. [8] (b) Test track in winter 2018 before a measurement. [8] (c) Test section on E8/Vt21 in Muonio. On the left and right side are reflector poles. (Händel C, Saarenpää T & Autioniemi M, 2019)



Figure 7. Test field in Muonio. (a) A representative empty foundation for a reflector pole (concrete holder, grey). (b) The selected road section in Muonio including 189 pole holders. The red coloured dots show empty holders while the green coloured dots show reflector locations. (c) Overview of conditions at the test tracks. (Händel C, Saarenpää T & Autioniemi M, 2019)

Applied Radar System - ARS 408-21 from Continental AG

Continental's premium radar sensor 408-21 is designed for automotive applications. The sensor operates with a dual scan (serially alternating) at 77 GHz. The dual scan facilitates switching between short- and far-range mode (see Figure 8). Furthermore, the radar sensor contains multiple antennas for the simultaneous detection of targets. In order to protect the sensor from moisture, the radar was enclosed in a plastic box. In mobile measurements, the plastic box was further equipped with a holder to fix it to the front of the test vehicle. Prior to an experiment, the radar was connected to a CAN module providing the communication between the radar and the computer. A PLC was used to display the collected data on a screen. (Händel C, Saarenpää T & Autioniemi M, 2019)

The ARS 408-21 radar is based on FMCW modulations, realising the independent velocity and distance monitoring of objects in one measurement cycle. The objects' information is calculated in every cycle and the position is displayed in a coordinate system relative to the radar sensor. A technical description of the radar sensor is given in [9]. Besides the 408-21 Premium sensor from Continental, two other radar systems from Furuno Electric Co., Ltd. and Texas Instruments Inc. (TI) were tested regarding accuracy, resolution, data output and handling [8]. All three radars are suitable for transport applications. (Händel C, Saarenpää T & Autioniemi M, 2019)

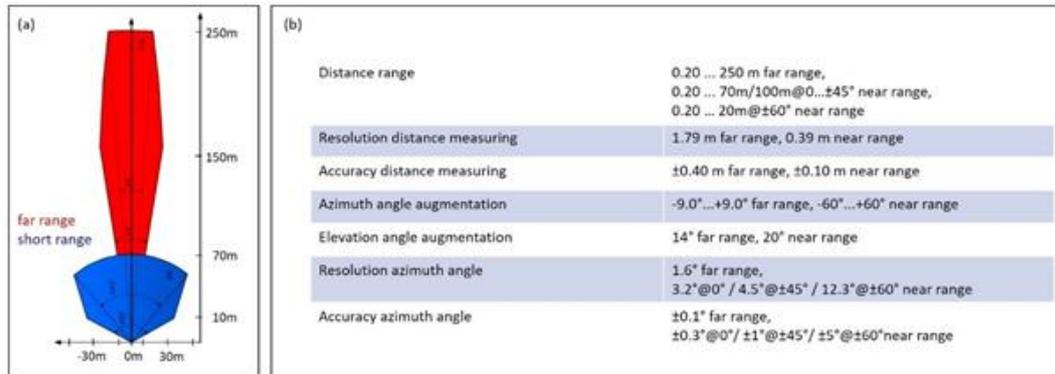


Figure 8. ARS 408-21 radar sensor. a) The digital antenna offers two independent scans for far and near range. The sensor contains 2 TX and 6 RX antennas for near-range and 2 TX and 6 RX antennas for far-range scan using digital formed beams. [8, 10] (b) Selected information from the datasheet. [10] (Händel C, Saarenpää T & Autioniemi M, 2019)

Applied Radar Reflectors

For the later described experiments, four radar reflectors from the maritime sector were selected and acquired. The chosen models are shown in **Figure 9**. The first and third reflectors are octahedral-shaped and have a diameter of ≈40 cm. Both consist of aluminium panels which are locked in place by plastic corners. The second reflector is a tubular reflector. The model consists of longitudinally arranged dihedrals in a transparent plastic cover. The fourth tested model is the Echomax EM180. It is vertical stack of three aluminium corner arrays enclosed in a plastic cover. The results and conclusions of a performance investigation of the reflectors are presented in [11]. (Händel C, Saarenpää T & Autioniemi M, 2019)



Figure 9. Radar reflectors used in the maritime sector. A selection of four radar reflectors used in the maritime sector is presented. [8] (Händel C, Saarenpää T & Autioniemi M, 2019)

In order to develop more practicable, cheaper and quick-to-produce radar reflectors, Lapland UAS designed and acquired four different octahedral corner reflectors. The principle of the self-designed corner reflectors is shown in Figure 10a. Extra-large (Ø 20 cm), large (Ø 10 cm), medium (Ø 4.05 cm) and small (Ø 1.649 cm) prototypes made from aluminium were designed (10 respectively, Figure 10b). For some preliminarily experiments, the reflectors were fixed on plastic poles (Figure 10c). (Händel C, Saarenpää T & Autioniemi M, 2019)

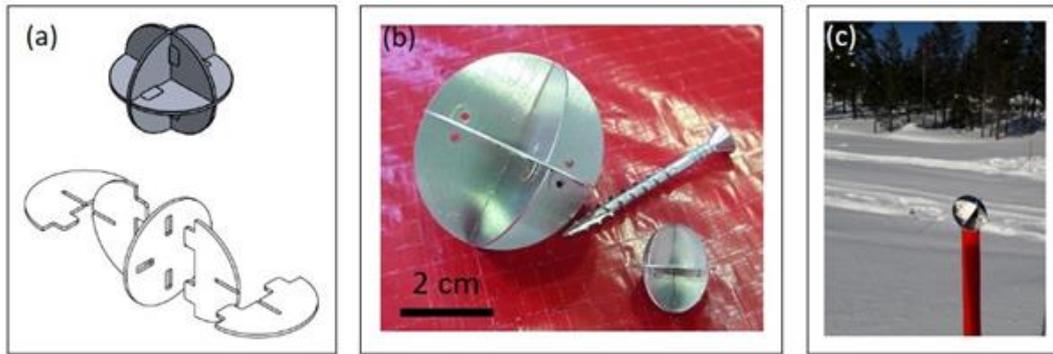


Figure 10. Self-designed aluminium radar reflectors. (a) Sketch and design drawing of the self-designed corner reflectors. [8] (b) Medium (left) and small (right) self-designed corner reflector. One prototype of each is shown. [8] (c) Self-designed corner reflector (medium version) on top of a plastic pole (60 cm high). [8] (Händel C, Saarenpää T & Autioniemi M, 2019)

Based on the tested reflectors, a tubular reflector pole was developed. It consists of a plastic pipe and an enclosure containing three $\varnothing 20$ cm corner reflectors (Figure 11a). The three reflectors can be rotated against each other and positioned along the same axis in the tube to optimise visibility. A plastic cover protects the single reflector plates from falling snow. The reflector design was developed according to our previous results, indicating that snowcovered reflector plates negatively affect the reflectors' visibility [8]. A pole height of ≈ 1.8 m above the ground was chosen to avoid the reflector being covered by snow. A selection of the self-designed tubular reflector poles in the test field in Muonio is shown in Figure 11b. Altogether, 100 tubular reflector poles were manufactured and 97 of them were installed on the left and right side of the road. Figure 11c illustrates the experimental set-up in Muonio. (Händel C, Saarenpää T & Autioniemi M, 2019)



Figure 11. Self-designed reflector poles. (a) Self-designed tubular reflector pole containing three $\varnothing 20$ cm corner reflectors. A plastic cover (brown) protects the single reflector plates from falling snow. (b) 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) Sketch of the experimental set-up in Muonio. Shown is the position of the radar (yellow) on the road. The red dots on the left and right side illustrate ten representative reflector poles. (Händel C, Saarenpää T & Autioniemi M, 2019)

Test Vehicle and Test Plan

The measurements on the test track in Muonio were carried out with the Road Doctor Survey Van (RDSV). The RDSV is a non-destructive survey system designed for road condition data collection and analysis. In our tests the RDSV was equipped with the RD CamLink-system, the RD Laser Scanner with a 3D accelerometer, IMU capable GPS and the ARS 408-21 radar sensor from Continental (**Figure 12a**). (Händel C, Saarenpää T & Autioniemi M, 2019)

The RD CamLink-system is designed to collect videos, audio commentary and drainage or pavement distress inventories on the road, together with GPS coordinates. The main components of the RD CamLink-system are two (out of a possible three) GigE connected industrial colour cameras (up to 30 images per second) protected by enclosures (**Figure 12b**), a GPS device and a laptop. Both cameras were fixed with a mounting system on the roof of the RDSV. Location information could be collected simultaneously with other survey data using the Road Doctor® CamLink program with GPS and DMI (accuracy better than 0.1 m). In addition to the radar and camera system, the data collection was carried out using a SICK LMS511 laser scanner (**Figure 12c**). The laser scanner was mounted at the back of the survey van. Based on the laser scanning data, a 3D profile of the road and the surroundings can be produced, and the position of the radar reflector poles can be displayed on a map. The scanning range is up to 65 m. The laser scanner data was measured simultaneously with a 3D accelerometer, GPS and digital image data using RD CamLink. (Händel C, Saarenpää T & Autioniemi M, 2019)

The Road Doctor® software was used in the field data collection, data processing and analysis. It was further applied to check and validate the data positioning quality. This software facilitates integrated analysis of the laser scanner data together with videos and maps. The software was developed by Roadscanners Ltd. (Händel C, Saarenpää T & Autioniemi M, 2019)



Figure 12. Road Doctor Survey Van. (a) Road Doctor Survey Van in a field test. The van is equipped with (1) the ARS 408-21 radar sensor from Continental, (2) the RD CamLink - system and, (3) the SICK LMS511 laser scanner in a close-up. (b) GigE connected industrial colour cameras. (c) SICK LMS511 laser scanner. (Händel C, Saarenpää T & Autioniemi M, 2019)

For the experiments on the test track in Muonio a test plan was developed. Results of pre-testing and knowledge gained from previous field tests were utilized to find different test scenarios for the mobile road tests in Muonio. The objective was to define several test scenarios that would mimic real situations that occur in everyday traffic. The plan contains tests at different speeds (30, 60 and 80 km/h) and in different directions. "Direction 1" stands for driving towards Muonio (from south to north) and "Direction 2" means driving away from Muonio (from north to south). The test plan described in **Figure 13** gives an overview of the defined scenarios. (Händel C, Saarenpää T & Autioniemi M, 2019)

Test Number	Direction	Speed [km h ⁻¹]	Poles	Comments	Test Number	Direction	Speed [km h ⁻¹]	Poles	Comments
1	1	30	no	few cars	12	2	80	yes	no cars
2	2	30	no	few cars	13	1	80	yes	Right side of the lane, one car
3	1	60	no	no cars	14	2	80	yes	Right side of the lane, one car
4	2	60	no	no cars	15	1	80	yes	Left side of the lane, no cars
5	1	80	no	truck outside track	16	2	80	yes	Left side of the lane, no cars
6	2	80	no	few cars	17	1	80	yes	zig zag, few cars
7	1	30	yes	few cars	18	2	80	yes	zig zag, no cars
8	2	30	yes	no cars	19	2	80	yes	behind a car
9	1	60	yes	two cars passed by	20	1	80	yes	car passing by
10	2	60	yes	no cars	21	2	80	yes	blow snow
11	1	80	yes	few cars	22	2	80	yes	behind a truck

Figure 13. Test plan from the test track in Muonio.

2.1.3 Results and Discussion

2.1.3.1 Summary of the Field Tests Performed in 2017/18

The practical tests of this field study were carried out on the test track in Rovaniemi during the winter period 2017/18. All presented results were published and discussed in the publication series of research reports and compilations of Lapland University of Applied Sciences Ltd (Lapland UAS) [8]. Three radar systems suitable for transport applications were tested: The system from Continental AG, Furuno Electric Co., Ltd. and Texas Instruments Inc. (TI).

Test Field Background and the Influence of Human Presence on the Radar Signal

First, reference measurements were conducted with each radar. The characterisation of typical objects in the surroundings concerning their RCS was the aim of these tests. In these experiments the test field only, without humans or equipment, was monitored (61 s, 136 data point/10 s). The experimental results show that the test field is free from reflecting objects with $\sigma < 16 \text{ m}^2$. It is concluded that 16 m^2 is an adequate threshold for the detectability of objects in further experiments. The test field background measured with the radars from Continental, TI and Furuno are shown in [8]. (Händel C, Saarenpää T & Autioniemi M, 2019)

Further, the impact of humans on the radar signal was investigated with the three radars. In these tests a human, dressed in winter clothes, walked along the test track. Other reflectors were not present during the experiment. Humans could not be detected, either stationary or walking, with the selected noise level of $\sigma = 16 \text{ m}^2$. The results are summarised in Figure 14. The described results lead to the conclusion that pedestrians will not influence the tests performed with the chosen set-up significantly. [8] (Händel C, Saarenpää T & Autioniemi M, 2019)

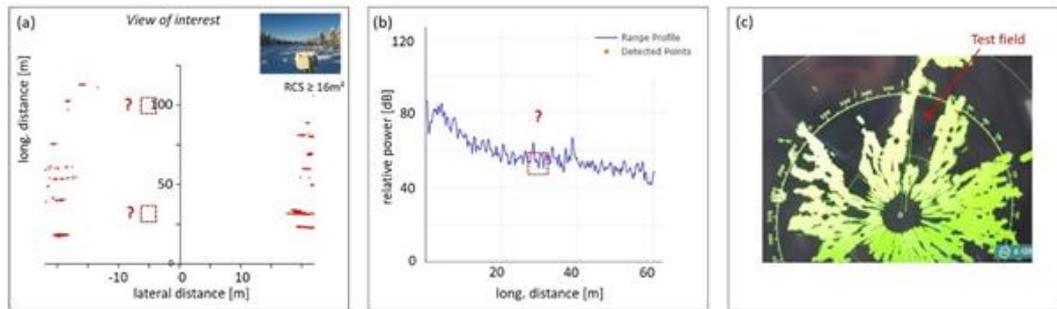


Figure 14. Test Field Background and the Influence of human presence. (a) Longitudinal - lateral distance graph of the test track measured with the ARS 408-21 sensor from Continental. The graph shows only reflections (red dots) with RCS of 16 m² or higher. On the left and right edge of the test field, multiple strong reflections are visible. These reflections are caused, among other things, by large trees and wires in the test track's surroundings. The red boxes in the centre of the plot show two positions where a human stood during the measurement (64 s). [8] (b) Range profile detected with the radar from TI. The position of the human is marked with a red box. [8] (c) Display screenshot of the NavNet TZtouch2 (Furuno) during an experiment. The black rectangle shows the test field with the surrounding area. [8] (Händel C, Saarenpää T & Autioniemi M, 2019)

Radar and Reflector Tests

First, the octahedral, circular 40 cm reflector (**Figure 15a**) was monitored with the ARS 408-21 from Continental on different longitudinal positions (**Figure 15b**). Each position was measured (60 s) in a separate test. The reflections are displayed as red points and their RCSs range from $\sigma(80\text{ m}) = (18 \pm 3)\text{ m}^2$ to $\sigma(60\text{ m}) = (794 \pm 113)\text{ m}^2$. This deviation is based on the RCS' angle dependency. The detected accuracy is $\pm 0.2\text{ m}$ in a lateral and $\pm 0.1\text{ m}$ in a longitudinal direction [8]. Besides the octahedral, circular 40 cm reflector, three other reflectors were analysed regarding detectability with the system from Continental. The test results are summarised in the upper table of **Figure 15c**. All four tested reflectors were also detectable with the radars from TI and Furuno. A detailed description of the experiments is shown in [8]. (Händel C, Saarenpää T & Autioniemi M, 2019)

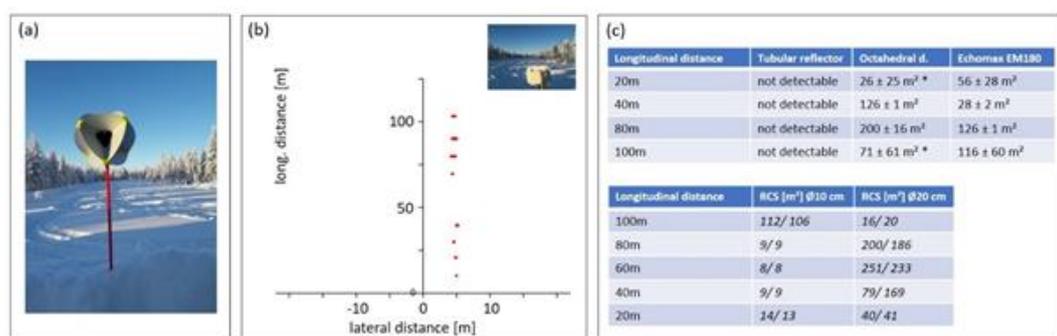


Figure 15. Different radar reflectors tested with the 408-21 Sensor from Continental. (a) The octahedral, circular 40 cm reflector on a 60 cm high plastic pole while testing. [8] (b) Longitudinal-lateral distance plot measured with the Continental radar. The red dots show selected reflections caused by the octahedral circular 40 cm reflector. Each reflection was measured in a separate experiment. [8] (c) Behaviour of different radar reflectors measured with the system from Continental. Each reflection was measured in a separate test. (Upper table) Median RCS values (Median \pm SD) measured in four different distances with the radar from Continental. (Lower table) Self-designed reflectors tested with the Sensor from Continental. Median and mean RCS values measured at five different distances. [8] (Händel C, Saarenpää T & Autioniemi M, 2019)

In a second experimental set-up, the octahedral circular 40 cm reflector was shifted in the test field. The test demonstrates that the corner reflector is quasi-constantly detectable with all three radars, while it is being moved (Figure 16). These positive results provide the basis for further tests involving a moving vehicle. Figure 16c demonstrates the angle dependency of the RCS during the shift of the reflector. During the 100 s reflector shift, the RCS values fluctuate between around zero and 400 m². The result is in accordance with theoretical expectations. (Händel C, Saarenpää T & Autioniemi M, 2019)

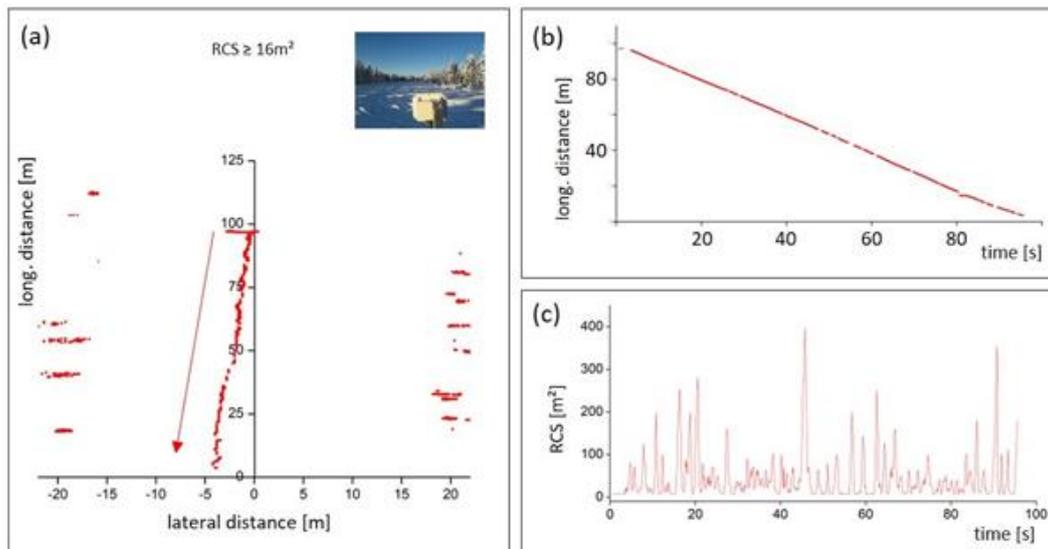


Figure 16. Shifted octahedral, circular 40 cm corner reflector measured with the radar from Continental. (a) Longitudinal-lateral distance plot. The reflector was moved from a position 100 m away from the radar towards the radar. The red arrow shows the direction of movement. [8] (b) Longitudinal distance-time plot. [8] (c) RCS-time plot. [8] (Händel C, Saarenpää T & Autioniemi M, 2019)

Besides the reflectors used commercially, four types of self-designed corner reflectors were analysed with the radar from Continental. The smaller (\emptyset 1.7 cm and \emptyset 4 cm) self-designed corner reflectors could not be detected at all. The RCSs of the self-designed \emptyset 20 cm reflector and the octahedral circular 40 cm reflector from the maritime sector are in the same order of magnitude (lower table in Figure 15c). Based on these results, it is concluded that our self-designed \emptyset 20 cm reflectors are a cheap and quick-to-produce alternative for our purposes, compared to current products on the market. [8] (Händel C, Saarenpää T & Autioniemi M, 2019)

Road-like Case and Mobile Tests Performed with the ARS 408-21 from Continental

The experiments described in the first part of this chapter build the basis for tests with a moving vehicle. The experimental set-up (Figure 17a and 17b) consisted of ten self-designed \emptyset 20 cm reflectors (five on the left side and five on the right). The reflectors were attached on top of plastic poles. A longitudinal distance of 20 m between the poles was chosen based on the specifications of the radar from Continental (3 reflector poles per side are in the near range area of the radar) [10]. The location of the radar was chosen to be similar to that of a car on a road. The measured mean and median RCSs are given in the table in Figure 17a. [8] (Händel C, Saarenpää T & Autioniemi M, 2019)

For the mobile test, the same experimental set-up as before was used. While testing, the radar from Continental was mounted on the front of a van (see Figure 12a). Figure 17c shows the condition before the van drove through the set-up. The radar reflectors appear as points on the left and right sides. The ten corner reflectors were simultaneously measured in one test. The vehicle's starting position was selected as sketched in Figure 17a. Ten seconds after the data collection had begun, the van drove ($v \approx 6.5$ km/h) through the set-up. Figure 17d shows the time evolution of the lateral distance during the measurement. The results show that not all reflectors were detectable the whole time while the van was driving along the test track. But at least five self-designed reflectors were always detectable and guaranteed adequate tracking of the test road. Moreover, the tests show a strong angle dependency of the RCS for the individual reflectors (Figure 17e). [8] (Händel C, Saarenpää T & Autioniemi M, 2019)

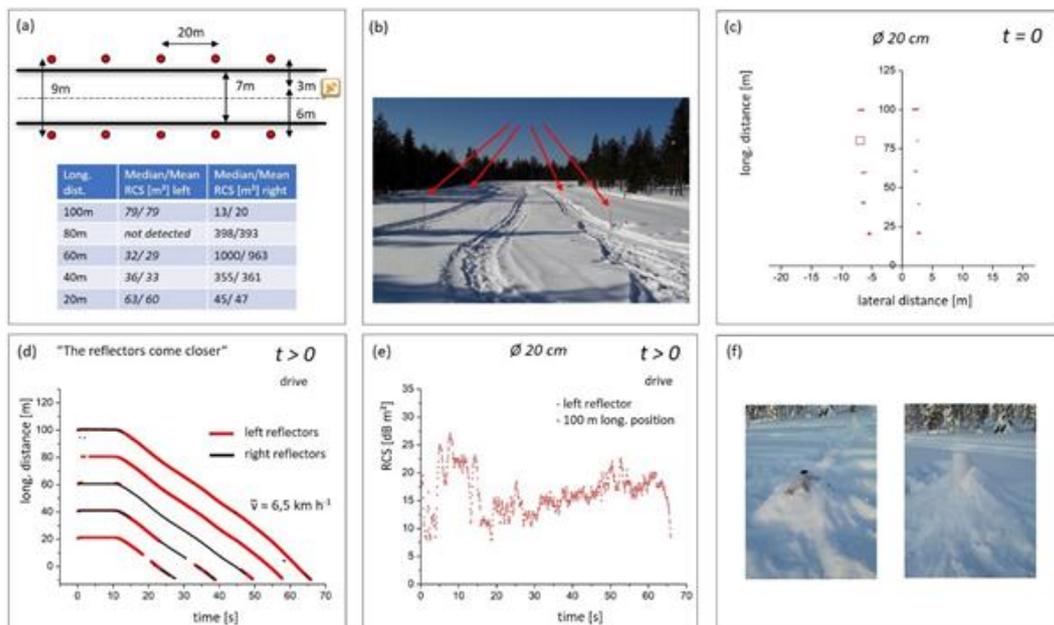


Figure 17. Self-designed radar reflectors in a road-like case and in a mobile test. a) (upper:) Set-up in the test field. The longitudinal distance between the reflectors (red dots) is 20 m respectively. The reflectors are positioned 1 m away from the edge of the hypothetical road. The radar's position is marked in yellow. (lower:) All ten reflectors were simultaneously measured in one static experiment. (b) Photograph of the set-up. The red arrows point towards the reflectors on the plastic poles. (c) Longitudinal-lateral distance plot of the set-up before the vehicle started to drive. The red dots show the measured reflections caused by the reflector. (d) Longitudinal distance-time plot for all 10 reflectors simultaneously. The five reflectors on the right side are coloured in black and the reflectors on the left side in red. (e) RCS time plot for a representative reflector during mobile measurement. (f) Selection of test cases with the radar from Continental. The longitudinal distance between radar and reflector was 20 m (5 m lateral). (Händel C, Saarenpää T & Autioniemi M, 2019)

The Influence of Snow and Roadside Furniture on Radar Reflectors

In this chapter, the effect of snow and roadside furniture on the radar signal is discussed. At the beginning, the four reflectors from the maritime sector were positioned 20 m and 80 m (in longitudinal direction) away from the radar, in the test field. Each reflector was tested in a separate experiment. After accurate positioning, the test field was monitored for 60 s with radars from Continental and TI. After that, the reflectors were slowly covered by snow in multiple steps and their detectability was constantly monitored. It was found that densely packed snow had a very strong influence on the detectability of all tested reflectors, independently of the radar system used. In contrast, moderate falling snow did not significantly affect the detectability of the reflectors. Figure 17f demonstrates a selection of test cases performed with the radar from Continental. (Händel C, Saarenpää T & Autioniemi M, 2019)

In order to study whether typical roadside furniture has a notable effect on future mobile measurements, a lamp pole and poles of different material were illuminated with the radar systems from Continental and TI. The lamp, as a typical representative of roadside furniture, could neither be detected with the radar from Continental, nor with the radars from TI or Furuno. These results indicate that typical roadside furniture, such as lamp poles, are not practicable as proper radar reflectors for the tested radar systems. Further, three circular metal poles composed of different material were tested. All three tested poles were not, or were only weakly, detectable with the radars. The detected signal strength is from one to two magnitudes smaller than some of the tested corner reflectors. It can be concluded that metal pipes are not practicable as radar reflectors for the tested radar systems. (Händel C, Saarenpää T & Autioniemi M, 2019)

2.1.3.2 Field Tests Performed in Muonio 2019

All practical tests presented in this chapter were carried out on E12/Vt21 in Muonio during the winter period 2018/19. The experiments discussed in this paragraph were carried out with our test vehicle including the radar sensor from Continental, the RD CamLink-system as well as a laser scanner.

The Test Field Background without Reflector Poles

In order to obtain comparable starting conditions for further experiments, reference measurements were performed without reflector poles on the left and right sides of the road. In these experiments the test section in Muonio was monitored by the radar and cameras while the vehicle drove at different speeds through the test section. While measuring, the radar sensor from Continental was mounted on the front and the cameras on the roof of the vehicle. The characterisation of typical objects in the surroundings and roadside furniture is an important goal of this measurement. (Händel C, Saarenpää T & Autioniemi M, 2019)

Figure 18a demonstrates a section of the 1.5 km-long test field in Muonio without the reflector poles. The map shown in the figure is from the National Land Survey of Finland WMS server. The surroundings of the road are characterised by multiple radar reflections (blue spots). These reflections are caused by, among other things, large trees and house roofs. The road itself is free of radar reflections. Figures 18b – 18d show different types of radar-reflecting objects

such as parked cars, snow poles and street signs. The detected signal strengths of the objects are summarised in Figure 18e. The measured values range from $\sigma = (11 \pm 0.7) \text{ m}^2$ to $\sigma = (16 \pm 1.5) \text{ m}^2$. Based on previous results, we expect significantly stronger signals backscattered from our self-designed reflector poles. (Händel C, Saarenpää T & Autioniemi M, 2019)

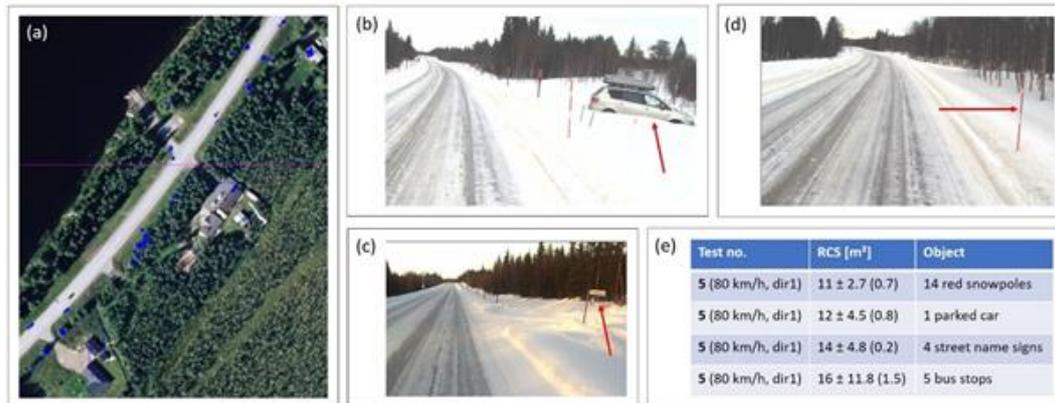


Figure 18. Test field background in Muonio. (a) Map of a selected part of the test field in Muonio. The blue dots show radar reflections produced by objects along the roadside. (b-d) Typical radar reflecting objects along the road. The objects include a parked car, several street signs and snow poles. The pictures are screenshots taken from the RD CamLink system. (e) Mean RCS values (Mean ± SD (SEM)) measured for the different objects. The values shown in the table are measured at 80 km/h in direction 1. (Händel C, Saarenpää T & Autioniemi M, 2019)

Further, different objects along the roadside were detected at different vehicle speeds. The selected speeds were 30 km/h (similar to former test cases in Rovaniemi), 80 km/h (maximum speed allowed on the test track during the wintertime), and 60 km/h. **Figure 19a** shows the test results for a distance table. The results indicate that higher vehicle speeds lead to lower detected RCS values. The RCS time plot shows, that at higher speeds, peak values were less frequently detected. This leads to lower RCS mean values and especially in the near range area to smaller standard deviations at higher speeds. Near range area means longitudinal distances up to 70 m. The lower graph in **Figure 19a** shows the time evolution of the RCS while the vehicle drove along the road. The oscillation of the RCS is based on its angle dependency. While driving, the angle between the radar and the reflector naturally changed due to the shifting path. **Figure 19b** shows the corresponding longitudinal distance time plot of the radar reflections, caused by the distance table, while the vehicle drove along the road. The figure demonstrates that the distance table is always detectable in the near and far range area. In the far range area, the radar lost the connection to the distance table for 2 s ($v = 30 \text{ km/h}$). During these 2 s the sightline between vehicle and table was blocked by a truck. Similar results were obtained from a bus stop (**Figure 19c**). (Händel C, Saarenpää T & Autioniemi M, 2019)

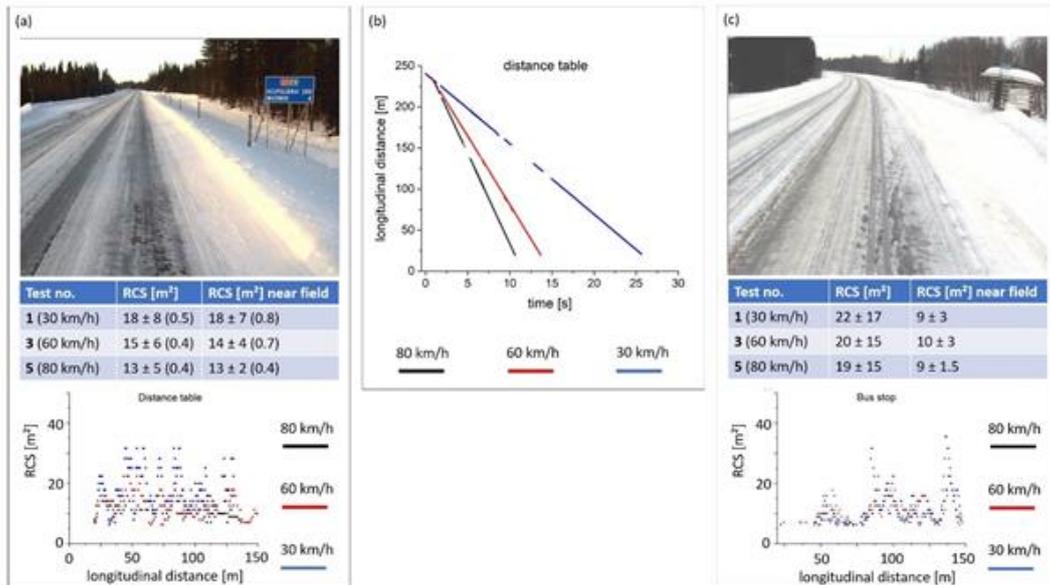


Figure 19. Test field background in Muonio measured at different vehicle speeds. (a) Mean RCS values measured in a distance table at different speeds (table). The values shown in the table are measured in direction 1. The values are shown in the form: Mean ± SD (SEM). The picture is a screenshot made with the RD CamLink system. The lower graph shows the time evolution of the RCS for the distance table while the vehicle drove along the road. (b) Corresponding longitudinal distance time plot of the distance table (near and far range area). (c) Time evolution and mean values of the RCS (Mean ± SD) measured for a bus stop at different speeds. The values shown in the table are measured in direction 1. (Händel C, Saarenpää T & Autioniemi M, 2019)

Test Field with Reflector Poles

Based on the results obtained in 2017/18, mobile experiments with the test vehicle were performed on the test track in Muonio. Prior to the experiments, the 1.5 km-long test track was prepared as described. The test track includes 97 self-designed tubular reflector poles on the left and right sides of the road (pairwise in most cases). Figure 20a demonstrates a section of the test field in Muonio including the reflector poles. The map shown in Figure 20a is from the National Land Survey of Finland WMS server. The presented radar reflection points on the map (blue dots) were calculated using the distance and the offset provided by the radar as well as the GPS-position provided by the GPS and the IMU connected to the Lidar. Due to GPS and IMU not being connected directly to the radar, small positioning errors were introduced by the set-up, especially at longer distances. (Händel C, Saarenpää T & Autioniemi M, 2019)

Figure 20b shows a longitudinal distance-time plot, including all 97 reflectors simultaneously. The data was produced while our test vehicle drove through the test field at 80 km/h in direction 1 (from south to north). The test was repeated under the same experimental conditions, but the test vehicle drove in direction 2 (Figure 20c). It should be noted that most of the single linear graphs represent two reflector poles at the same longitudinal position (one on the left and one on the right side of the road). While measuring, the sensor from Continental was mounted on the front and the cameras on the roof of the vehicle. The test field was continuously monitored with the radar while the vehicle drove. (Händel C, Saarenpää T & Autioniemi M, 2019)

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 previous tests in Rovaniemi were carried out at a maximum speed of 30 km/h. Short losses of contact between individual reflectors and the radar are caused by other vehicles blocking the signal. It was further found that reflector poles on the right side of the test vehicle send a stronger back-scattered 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 RCS mean values (signal strengths) for the poles are $\sigma_{\text{right}} = (65 \pm 4.9) \text{ m}^2$ and $\sigma_{\text{left}} = (49 \pm 3.3) \text{ m}^2$. 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 to three times larger. The data shows further smaller standard deviations for the detected RCS in the near range area compared to long distance measurements. (Händel C, Saarenpää T & Autioniemi M, 2019)

The green graph in **Figure 20b** shows reflector pair number 11. This reflector pair is analysed in the next chapter.

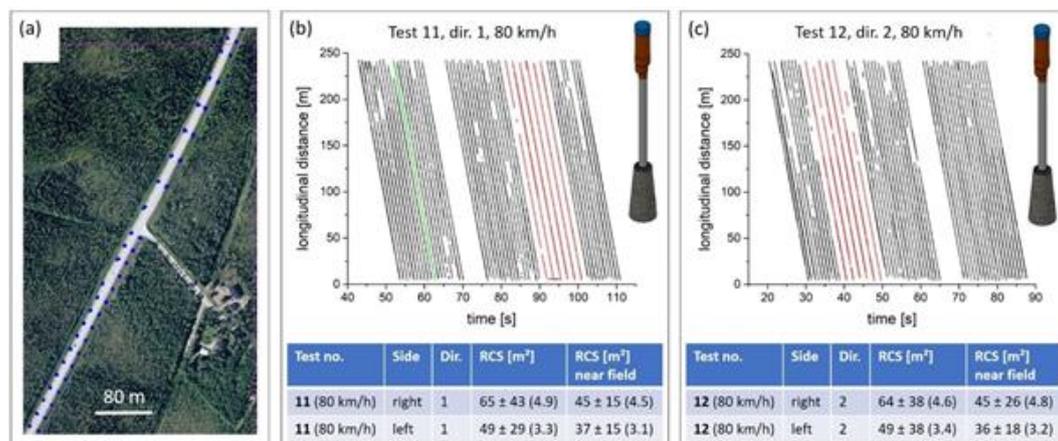


Figure 20. Mobile test with 97 self-designed tubular reflectors. (a) Map of a selected part of the test field in Muonio. The blue dots show radar reflections produced by our self-designed tubular reflector poles on the left and right sides of the road. The longitudinal distance between the reflector poles is 20 m in the lower part of the figure and 40 m in the upper part. (b) Longitudinal distance-time plot for all 97 reflectors simultaneously. Most of the linear graphs represent two reflectors (one on the left and one on the right side) respectively. The red graphs represent poles with a longitudinal distance of 40 m while the black graphs represent poles with a distance of 20 m. The green graph shows the reflector pair number 11. The lower table shows weighted mean RCS values measured for all 97 self-designed reflector poles (separated by left and right side). The values are shown in the form: Mean ± SD (SEM). (c) Same content as in (b) but the test vehicle drove through the set-up from the opposite direction. (Händel C, Saarenpää T & Autioniemi M, 2019)

Influence of the Driving Speed on Positioning and RCS

Studying the influence of the test vehicle's speed on the positioning of our self-designed tubular reflectors is a further essential goal of this study. Figure 21 shows a qualitative analysis of positioning for one individual reflector pole measured at $v = 30$ and 80 km/h respectively. The spreading of the radar reflection values was measured manually using a selection tool. The selection tool (ruler) is a feature which is integrated in the Road Doctor software. The data

shows that the positioning of the reflector poles is more accurate at lower vehicle speeds. 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, that means at longitudinal distances between 0 and 70 m, is on average more accurate than in the far range area. The measured data is in good accordance with [10]. (Händel C, Saarenpää T & Autioniemi M, 2019)

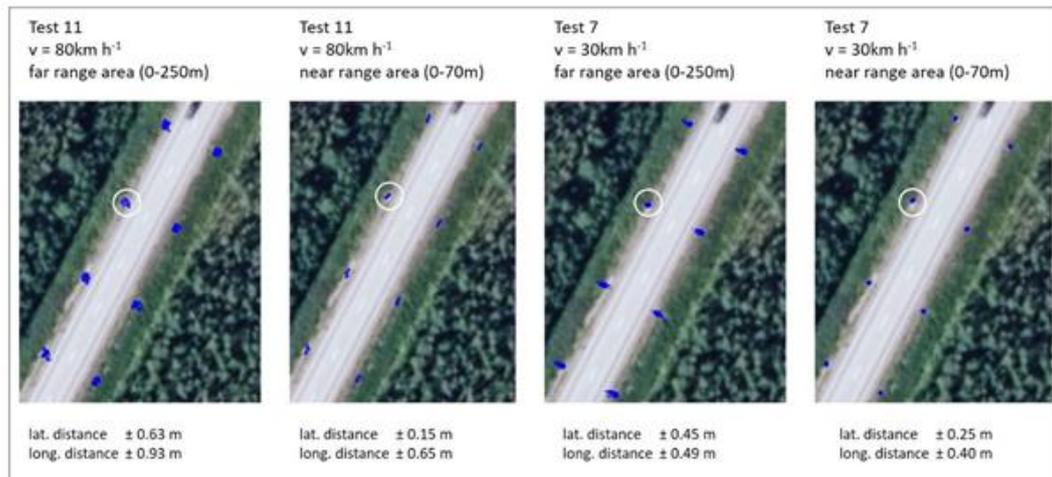


Figure 21. Influence of the driving speed on positioning. Map of a selected part of the test field in Muonio. The blue dots show radar reflections produced by our self-designed tubular reflector poles on the left and right sides of the road. The longitudinal distance between the reflector poles is 20 m. (Händel C, Saarenpää T & Autioniemi M, 2019)

Further, one individual self-designed reflector pole was detected at different vehicle speeds. The selected speeds were 30 km/h (similar to former test cases in Rovaniemi), 80 km/h (maximum speed allowed on the test track during the wintertime) and 60 km/h. Figure 22 shows the test results for the representative pole pair. Figure 22a shows the longitudinal distance-time plot of radar reflections caused by the selected pole while the vehicle drove along the road. The reflector was on the right side of the test vehicle that drove in direction 1. Figure 22c shows the same experimental set-up as in Figure 22a but the test vehicle drove in direction 2. Both figures demonstrate that the pole is detectable at all tested speeds in the near and far range area. Figure 22b and 21d show the corresponding RCS-longitudinal distance plots. The oscillation of the RCS values is based on the continuous change of the angle between radar and reflector pole while the vehicle was moving. Both figures show that at higher speeds, peak values are no longer detected. This leads to lower detected RCS mean values. The tables in Figure 22e and 22f summarise the corresponding RCS mean values (signal strengths) for the single pole measured at different driving speeds. The measured RCS mean values for the pole pair are $\sigma_{dir1} = (79 \pm 6) \text{ m}^2$ and $\sigma_{dir2} = (81 \pm 4) \text{ m}^2$ and thus four times larger than the detected objects along the roadside. (Händel C, Saarenpää T & Autioniemi M, 2019)

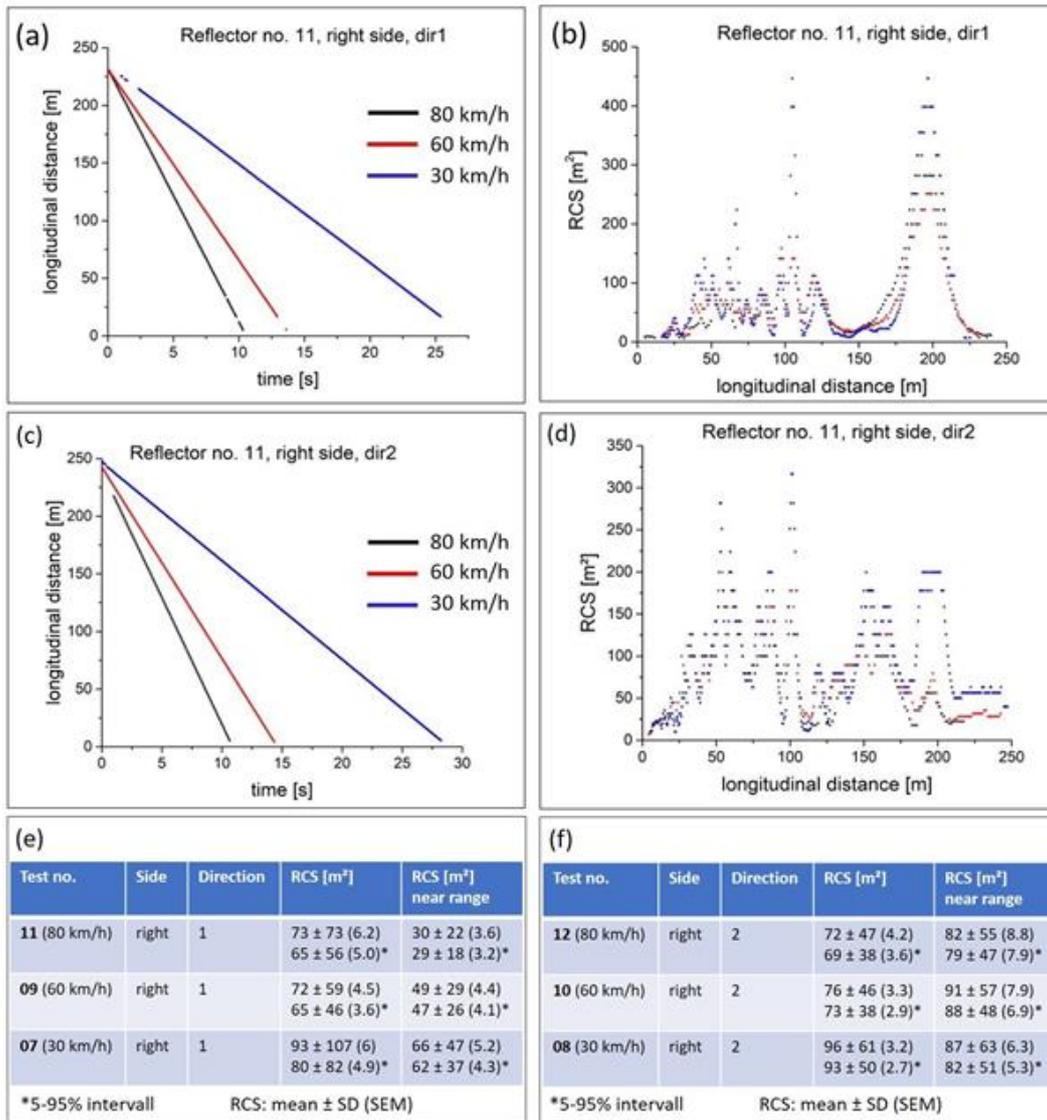


Figure 22. Influence of driving speed on the RCS. (a) Longitudinal distance-time plot for one individual reflector (number 11) measured at different driving speeds. The reflector was on the right side of the test vehicle that drove in direction 1. (b) Corresponding RCS-longitudinal distance plot for reflector number 11. (c-d) Same experiment as in (a) and (b) but the test vehicle drove in direction 2. (e-f) Corresponding mean RCS values measured for reflector pole number 11 at three different speeds. (Händel C, Saarenpää T & Autioniemi M, 2019)

Other Vehicles in the Test Field

In the following chapter, the effect of oncoming cars on the detectability of our self-designed tubular reflector poles will be discussed. Figure 23a shows a longitudinal distance-time plot, including all 97 reflectors simultaneously. The data was produced while the test vehicle drove through the test field at 80 km/h in direction 1 (from south to north). It should be noted that most of the single linear graphs represent two reflector poles at the same longitudinal position (one on the left and one on the right side of the road). While measuring, the sensor from Continental was mounted on the front and the cameras on the roof of the vehicle. The test field was continuously monitored with the radar while the vehicle drove. The two linear graphs coloured in red show two oncoming cars. The steeper slope of the oncoming cars (compared to the reflector poles) results from the higher relative speed between the oncoming car and our test

vehicle. Figure 23b shows a screenshot taken from the RD CamLink system of the two oncoming cars. It should be noted that due to the proper height of the camera on the roof of the test vehicle, the first oncoming car did not block the sightline between camera and reflector pole at any time. Figure 23c demonstrates the corresponding section of the test field in Muonio including the reflector poles (National Land Survey of Finland). Besides the radar reflections produced by the reflector poles on the left and on the right side of the road (blue dots), further reflections caused by two oncoming cars on the road are clearly visible. Figure 23d shows a zoom-in of Figure 23a including nine reflector poles on the left side of the test vehicle only. It can be seen that the radar lost the connection with reflector number 19 for ≈ 3 s (purple brace). The result is shown in more detail in Figure 24. The reason for the contact loss is shown in Figure 23e. The trailer on the second car blocked the sightline between the camera and reflector pole. It can be assumed that the trailer also blocked the signal between the radar and the reflector pole due to its position 60 cm above the ground. The measured RCS mean values for oncoming cars are $\sigma_{\text{car1}} = (86 \pm 6.6) \text{ m}^2$ and $\sigma_{\text{car2}} = (45 \pm 2.2) \text{ m}^2$ and thus they are in the range of our self-designed reflector poles (Figure 24). (Händel C, Saarenpää T & Autioniemi M, 2019)

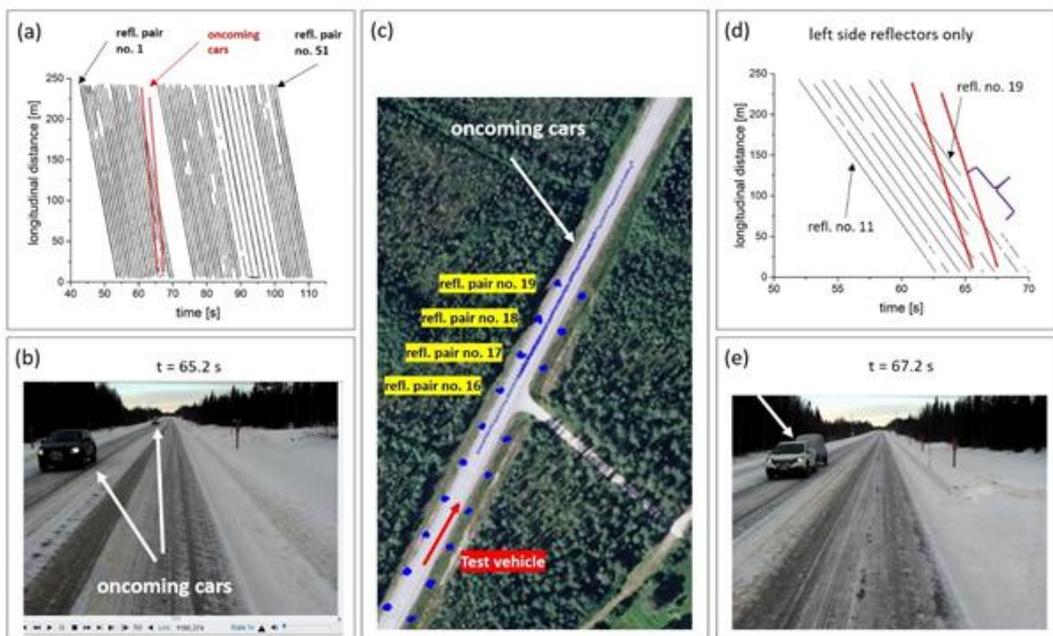


Figure 23. Two oncoming cars. (Test 11, dir1, $v = 80 \text{ km/h}$). (a) Longitudinal distance-time plot for all 97 reflectors simultaneously (black linear graphs). The two linear graphs coloured in red show two oncoming cars. (b) Screenshot taken with the RD CamLink system of the two oncoming cars. (c) Map of a selected part of the test field in Muonio. The blue dots show radar reflections produced by our self-designed tubular reflector poles on the left and the right side of the road. The longitudinal distance between the reflector poles is 20 m. The blue line in the centre of the road represents radar reflections produced by the two oncoming cars. The red arrow shows the driving direction of the test vehicle. (d) Longitudinal distance-time plot for nine selected reflectors simultaneously (black linear graphs). The nine linear graphs represent radar reflections produced by the reflector poles on the left side of the road only. The two linear graphs coloured in red show two oncoming cars. The purple brace shows the situation in which reflector pair number 19 (left side only) was blocked by the trailer of the second car. (e) The trailer of a car blocks the sightline to the reflector pole. (Händel C, Saarenpää T & Autioniemi M, 2019)

Finally, it can be stated that oncoming cars can be detected by the 408-21 radar sensor from Continental up to a longitudinal distance of 250 m. The detected signal strength of the cars is in the range of our radar reflectors. Particularly 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. In the present tests, oncoming cars could not block the sightline between radar and reflector poles on the right and the left side of the road simultaneously. (Händel C, Saarenpää T & Autioniemi M, 2019)

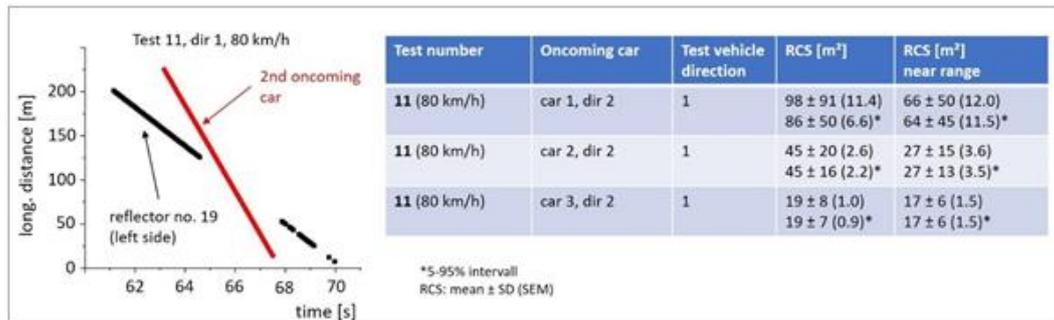


Figure 24. Oncoming car blocks the sightline to a reflector pole. Longitudinal distance-time plot for the left reflector of pole pair number 19 (black linear graph) and an oncoming car (red linear graph). The gap in the black graph shows the situation in which the reflector was blocked by the trailer of the second car (left). Mean RCS values measured for three different cars at a driving speed of 80 km/h (right). (Händel C, Saarenpää T & Autioniemi M, 2019)

Driving Behind a Truck – The Influence of snowdrifts

Studying the influence of snowdrifts on the detectability and the positioning of the self-designed reflector poles is an additional essential goal of the present study. For this purpose, a test scenario was created in which the test vehicle drove ≈ 30 m behind a truck. Due to the dry and cold weather conditions, the truck produced a trailing cloud of snow in which the test vehicle drove. (Händel C, Saarenpää T & Autioniemi M, 2019)

The photographs in Figure 25a and 25b show screenshots taken with the RD CamLink system at two different points in time during the test. The number of seconds in the upper left side of the screenshots characterise the length of time elapsed since the test has started. The two diagrams in Figure 25c and 25d show longitudinal distance-time plots for 49 reflectors simultaneously during the test drive (black linear graphs). The 49 black linear graphs represent radar reflections produced by the reflector poles on the right side of the road only. The green graph shows the truck in front of the test vehicle. The orange dashed line shows the position of the test vehicle when the corresponding screenshot was taken. The two diagrams show further that 55 seconds after the test has started, the test vehicle drove at a relatively constant distance of 30 m behind the truck. The data shows that the self-designed reflector poles could be detected at a longitudinal distance of up to 250 m under favourable conditions. Favourable condition means that the truck did not totally block the sightline to the poles (Figure 25a). However, detecting reflector poles at ≈ 100 m or greater longitudinal distances was not possible most of the time due to signal obstruction (Figure 25b). Moreover, the truck itself is a strong radar multi-reflector. The truck, with an RCS of over 10,000 m², is the strongest radar reflector that was detected during the whole study (Figure 25e). Another

important finding is a decreased RCS mean value (signal strength) of the reflector poles compared to a test without the truck (Figure 25c and 25e). The result indicates that snowdrifts weakens the detected RCS of the reflector poles. (Händel C, Saarenpää T & Autioniemi M, 2019)

Further, the influence of snowdrifts on the positioning of our self-designed tubular reflectors was investigated. Figures 25f and 25g show a qualitative analysis of positioning for one individual reflector pole. The spreading of the radar reflection values was manually measured by using a selection tool. The selection tool (ruler) is a feature that is integrated in the Road Doctor software. The data shows that the positioning of the reflector poles is less accurate if there are snowdrifts between the reflector poles and the test vehicle (radar). (Händel C, Saarenpää T & Autioniemi M, 2019)

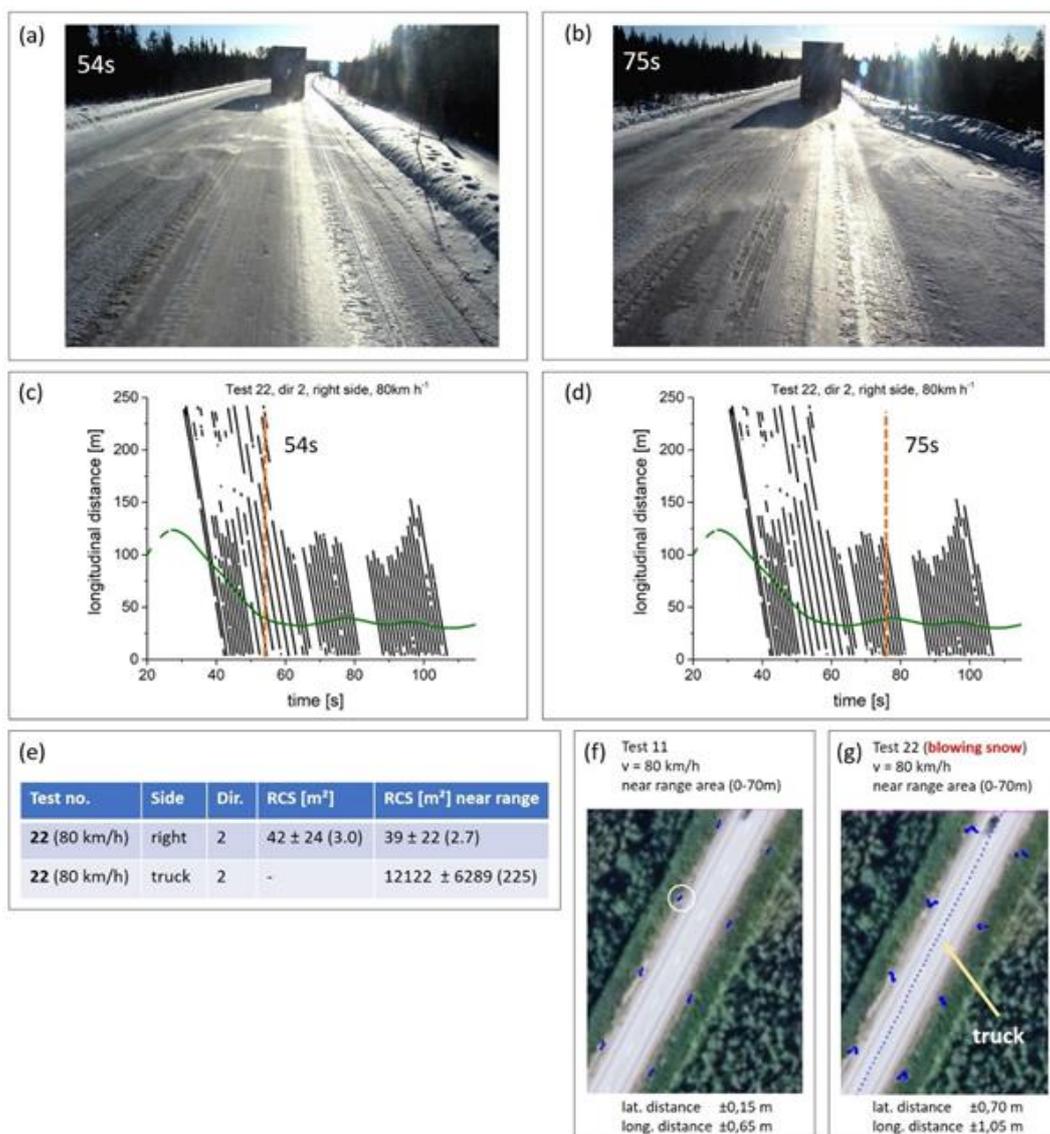


Figure 25. Driving behind a truck. (a) Screenshot taken with RD CamLink, 54 s after the measurement has started. (b) Screenshot taken with RD CamLink, 75 s after the measurement has started. (c) Longitudinal distance-time plot for all reflectors on the right side simultaneously (black linear graphs). The green graph represents the truck. The dashed orange line shows the position of our test vehicle when the corresponding screenshot was taken. (d) Longitudinal distance-time plot for all reflectors on the right side simultaneously (black linear graphs). The green graph represents the truck. The dashed orange line shows the position of our test vehicle when the corresponding screenshot was taken. (e) Table of RCS data. (f) Aerial view of Test 11. (g) Aerial view of Test 22 with blowing snow.

dashed orange line shows the position of our test vehicle when the screenshot was taken. (e) Mean RCS values (mean \pm SD (SEM)) measured for all 49 self-designed reflector poles (right side only) and the truck at a driving speed of \approx 80 km/h. (f) Map of a selected part of the test field in Muonio. The blue dots show radar reflections produced by our self-designed tubular reflector poles on the left and right sides of the road. The longitudinal distance between the reflector poles is 20 m. The test was performed without other cars in front of our test vehicle. (g) Same part of the road as in (f) but the test was performed while the test vehicle drove behind a truck. (Händel C, Saarenpää T & Autioniemi M, 2019)

References

- [1] Stetter R, Witczak M and Pazera M 2018 Virtual Diagnostic Sensors Design for an Automated Guided Vehicle *Applied Sciences* **8** 702
- [2] Teoh E R and Kidd D G 2017 Rage against the machine? Google's self-driving cars versus human drivers *Journal of safety research* **63** 57–60
- [3] Yin H and Berger C 2017 - 2017 When to use what data set for your self-driving car algorithm: An overview of publicly available driving datasets 2017 *IEEE 20th International Conference on Intelligent Transportation Systems (ITSC) 2017 IEEE 20th International Conference on Intelligent Transportation Systems (ITSC)* (Yokohama, 16.10.2017 - 19.10.2017) (IEEE) pp 1–8
- [4] Shabbir J and Anwer T 2018 *Artificial Intelligence and its Role in Near Future*
- [5] Rama Rao P V S, Gopi Krishna S, Vara Prasad J, Prasad S N V S, Prasad D S V V D and Niranjana K 2009 Geomagnetic storm effects on GPS based navigation *Ann. Geophys.* **27** 2101–10
- [6] Karthik Ramasubramanian B G 2017 *AWR1243 sensor: Highly integrated 76–81-GHz radar front-end for emerging ADAS applications*
<http://www.ti.com/lit/wp/spyy003/spyy003.pdf> (accessed 17 May 2018)
- [7] Google LLC 2018
<https://www.google.fi/maps/place/66%C2%B032'52.0%22N+25%C2%B048'36.0%22E/@66.547778,25.81439m/data=!3m1!1e3!4m5!3m4!1s0x0:0x0!8m2!3d66.547778!4d25.81> (accessed 17 May 2018)
- [8] Autioniemi M, Konttaniemi H and Händel C 2019 Detecting Passive Radar Reflectors for Automotive Applications: Aurora Arctic Challenge Field Tests in 2018 *LAPLAND UAS PUBLICATIONS*
- [9] Roland Liebske 2016 *ARS 404-21 Entry and ARS 408-21 Premium - Short Description: Technical Data* http://www.compotrade.ru/i/pdf/ARS404-21_AR5408-21_en_V1.03.pdf (accessed 1 Jun 2018)
- [10] Continental AG 2017 *ARS 408-21 Premium Long Range Radar Sensor 77 GHz*
https://www.continental-automotive.com/getattachment/5430d956-1ed7-464b-afa3-cd9cdc98ad63/ARS408-21_datasheet_en_170707_V07.pdf.pdf (accessed 24 May 2018)
- [11] Luke S 2007 Performance investigation of marine radar reflectors on the market.
- [12] Scherr S, Gattel B, Ayhan S, Bhutani A, Pauli M, Winkler W, Scheytt J C and Zwick T 2015 - 2015 Miniaturized 122 GHz ISM band FMCW radar with micrometer accuracy 2015 *European Radar Conference (EuRAD) 2015 European Radar Conference (EuRAD)* (Paris, France, 09.09.2015 - 11.09.2015) (IEEE) pp 277–80

2.2 Cooperative ITS

2.2.1 Background

Cooperative Intelligent Transport Systems (C-ITS) are ITS applications that are based on exchange of information between ITS stations that may be located e.g. in vehicles or in roadside environment. They usually integrate all the necessary data from public and private sources and develop relevant services for the users and also for the transport management purposes. C-ITS is a main step towards the development of automation in road transport.

Cooperative Intelligent Transport Systems (C-ITS) provide vehicle drivers and other road users with various services. One of the most important C-ITS applications is cooperative road safety which drivers perceive, in practice, as various traffic-related warnings. The deployment of C-ITS has been planned on the European level by, for example, the EU's C-ITS Platform and the Amsterdam Group which is a cooperation forum of various industries and member countries' authorities. The Amsterdam Group has drafted a list of C-ITSs whose specifications enable their implementation in Europe and that meet the objectives of transport policies specified for intelligent transport applications (so-called Day 1 applications).

The current situation of Day 1 applications and services as well as road transport automation and the measures required in the near future are discussed in Road Transport Automation: Road Map and Action Plan 2016–2020 (Lumiaho and Malin 2016).

There are various technologies for disseminating the messages required by Day 1 applications. The solution based on IEEE802.11p radio technology operated in the ITS-G5 frequency band has been standardised by ETSI. The LTE-V2X, C-V2X and 5G-V2X technologies based on mobile network utilisation as well as solutions for transmitting Day 1 messages using these technologies are currently under development, and the technologies' specifications are being prepared by ETSI. As there are various alternative technologies for transmitting Day 1 messages, the key questions are how to implement Day 1 services and the dissemination of their messages and how the different technologies support the functionality of the services. In addition, it is essential to identify the Day 1 services whose implementation is most feasible from the socio-economic point of view in the Finnish operating conditions.

This study was carried out as part of the Arctic Challenge project which in turn is part of the European NordicWay2 project. The results of the study have been presented tentatively at a NordicWay2 event (Öörni and Nykänen 2019) and in conference papers discussing the study (Kotilainen et al. 2019; Nykänen et al. 2018; Nykänen et al. 2019).

2.2.2 Objectives

The study's objective was to investigate various communication technologies for C-ITS in Finland's operating conditions in the Aurora Borealis Corridor located in the Finnish Lapland. The objective of Arctic Challenge was to "study solutions in road transport automation and intelligent infrastructure and their performance under arctic conditions". In its original form, the research question

on cooperative traffic data, which defines the study's content, consisted of three parts:

"Cooperative traffic information: How to implement C-ITS Day 1 hybrid services, that improve smooth traffic flow and the safety of transport, in the Aurora Borealis Corridor, and how functional are they from a technical perspective? Which Day 1 services should be implemented in the Aurora Borealis Corridor?"

The research question was drafted prior to commencing the study, and it served as the study's starting point in the initial stage until it was divided into more specific sections. The purpose of this was to enable the selection of most suitable methods for answering the research question and to enable providing separate results for each part of the original research question. Three separate research questions were formed on the basis of the original research question, and they are referred to as RQ1, RQ2 and RQ3:

RQ1: How to implement C-ITS Day 1 hybrid services, that improve smooth traffic flow and the safety of transport, in the Aurora Borealis Corridor?

RQ2: How functional are the services from a technical perspective?

RQ3: Which Day 1 services should be implemented in the Aurora Borealis Corridor?

The available technical solutions for implementation of Day 1 services examined in the study were an ETSI-standardised solution based on IEEE802.11p radio technology operated in the ITS-G5 frequency band and a solution based on mobile network and LTE technology.

2.2.3 Methods

Various methods were applied in the study in order to answer the research questions. Table 4 presents a concise summary of the methods used for answering each research question.

Table 4. Methods used for answering the research questions.

RQ1: "How to implement Day 1 services"	<ul style="list-style-type: none"> – Comparison of technologies (Testfest 3, "TF3") – Dynniq's expert opinion – Dialogue with stakeholders – Answers to RQ2 – Proof of Concept (TF1, TF2)
RQ2: "How functional are the services?"	<ul style="list-style-type: none"> – Proof of Concept (TF1, TF2) – Comparison of technologies (latency, robustness etc.) (TF3)
RQ3: "Which Day 1 services should be implemented?"	<ul style="list-style-type: none"> – Dynniq's expert opinion – Expert opinions on the scalability of the technologies – Expert opinions on the maturity of the technologies (Technology Readiness Levels, TRLs) – Relevant applications in the Aurora Borealis Corridor – Answers to RQ2

Three test periods (Testfests 1, 2 and 3) were organised during the study. Table 5 below presents the objectives of Testfests 1, 2 and 3.

Table 5. Objectives of Testfests 1, 2 and 3.

Test period	Objectives
Testfest 1	<ul style="list-style-type: none"> – Demonstration and test of a single Day 1 service (stationary vehicle warning) – Ensuring successful transmission of Day 1 messages to the test vehicle using IEEE80211p radio technology operated in the ITS-G5 frequency band – Testing the accuracy of Real-Time Kinematic (RTK) positioning – Integrating the automated vehicle for the field tests – Public demonstration in the AURORA area
Testfest 2	<ul style="list-style-type: none"> – Demonstration and test of two Day 1 services (stationary vehicle warning and roadworks warning) – Testing the hybrid solution that combines the IEEE802.11p and LTE technologies for transmission of messages from the vehicle to the back-office system (V2I) – Utilising a commercial and a private LTE network and the ITS-G5 technology in the implementation data transmission – Obtaining experience on the latencies of message transmission and the stability of applications – Generating data on the accuracy and functionality of RTK positioning
Testfest 3	<ul style="list-style-type: none"> – Demonstrating and testing four Day 1 services using implementations based on the LTE and ITS-G5 technologies (stationary vehicle warning, roadworks warning, reindeer warning and slippery road warning) – Measuring the communication latencies message transmission from vehicle to vehicle via cloud service and in message transmission from the back-office system to a vehicle

2.2.4 Test results

2.2.4.1 Testfest 1

Testfest 1 was organised between 15 and 19 January 2018 in Muonio as part of the Aurora Summit. The event took place in the yard area of Hotel Olos. The test architecture is presented in Figure 26. Testfest 1 focused on the transmission of Day 1 messages warning of slow or stationary vehicles from Dynniq's Cooperative and Connected Services Platform (CCSP) to automated vehicle Martti operated by VTT Technical Research Centre of Finland.

Setting up the temporary test environment in the yard area of Hotel Olos required considerable preparations. Dynniq's ITS-G5 on-board units were installed on the automated vehicle Martti, Indagon's Testlab vehicle and a passenger car (Figure 28). The ITS-G5 OBUs communicated with the C-ITS road side unit (RSU) which was temporarily installed in the area. The RSU was equipped with mobile data connection, and in addition to the on-board units, it communicated with Dynniq's CCSP located in the United Kingdom. After solving the initial challenges, Day 1 messages were successfully transmitted with a low latency in the C-ITS test environment.



Figure 28. Dynniq screen in the automated vehicle Martti.

The harsh weather conditions during Testfest 1 did not have any noteworthy effects on message transmission even though demanding winter conditions increase the risk of ice build-up on components exposed to weather (e.g. antennas), and low temperatures may hinder the operation of devices and components (e.g. screen components). The results of Testfest 1 indicate that a CCSP can provide the support functions of automated driving over long geographical distances. Testfest 1 provided new experience also to Dynniq, which supplied the test system.

Testfest 1 was the first occasion where Dynniq implemented and demonstrated Day 1 messages that warn of slow or stationary vehicles during the Arctic Challenge project. In the Testfest, a stationary vehicle formed a Cooperative Awareness Message (CAM) which was transmitted to Dynniq's CCSP via the RSU (Figure 29). Then, the Day 1 message warning of a slow or stationary vehicle was formed by the CCSP. The vehicle receiving the message displayed the warning using Dynniq's GreenFlow application. In the test, the GreenFlow application was installed on a tablet with the Android operating system. The warning was displayed as a graphic warning symbol. The driver was also shown the distance to the location which the warning concerned.



Figure 29. The installed Dynniq road side unit (RSU).

Indagon's task in Testfest 1 was to provide accurate positioning information and to support the test by providing the Testlab vehicle. The Testlab vehicle was equipped as a mobile office for the duration of the tests. RTK positioning base stations and mobile telecommunications links that were not available in other test vehicles were placed in the Testlab vehicle. Jointly with its subcontractor Ukkoverkot Ltd, Indagon was responsible for the operability of the private LTE network implemented in the Aurora pilot site. In certain areas, the private LTE network implemented by Ukkoverkot for the purposes of the test provided a reliable broadband connection and low-latency telecommunications links for the performed automated driving tests. In the Arctic Challenge project, the network built by Ukkoverkot was utilised in, for example, the implementation of the wireless telecommunications link used by Dynniq's C-ITS road side unit.

During Testfest 1, Indagon constantly monitored the accuracy of RTK positioning. According to the test results, current RTK positioning technology enables locating a vehicle with an accuracy of 1–10 cm in challenging arctic conditions.

2.2.4.2 Testfest 2

The focus of Arctic Challenge Testfest 2 was on testing Day 1 messages. Tests were performed for two different messages, slow or stationary vehicle warning and roadworks warning. Implementations based on ETSI's ITS-G5 technology and the LTE technology were tested for both warnings. The tests were performed in the Aurora pilot site in Muonio (Figure 30).

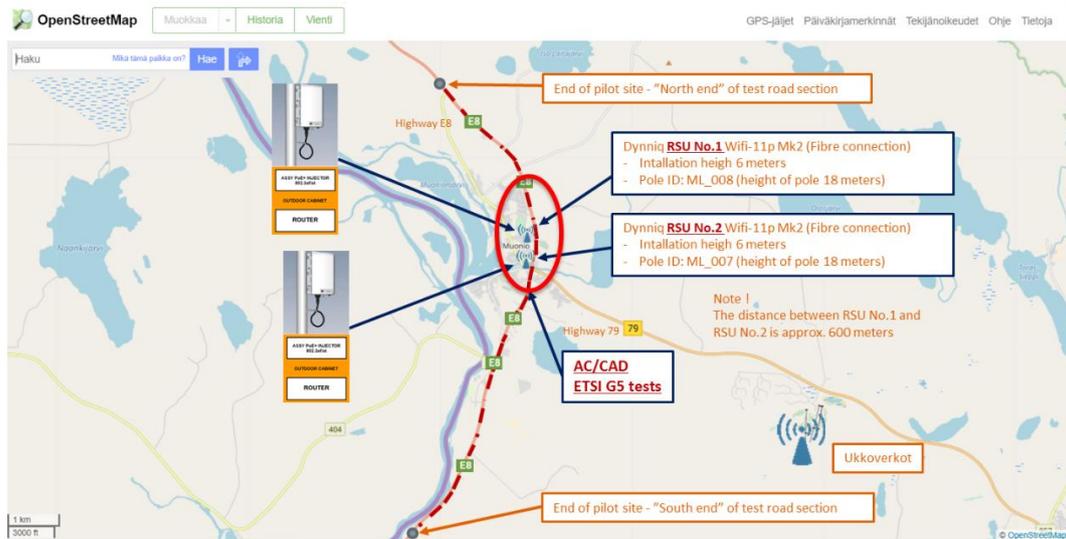


Figure 30. Testfest 2 – the section of the Aurora pilot site used in the tests.

The environment used for testing Day 1 messages during Testfest 2 is illustrated in Figure 31. The Day 1 messages were received using an ITS-G5 on-board unit which was connected to a tablet equipped with Dynniq's software. The implementation based on the LTE technology was tested with sets of on-board units including Android smart phones equipped with Dynniq's software. During Testfest 2, the Android phones were connected to telecommunications company Telia's commercial LTE network. The ITS-G5 on-board units communicated directly with C-ITS RSUs installed by Dynniq.

Connection between the RSU and Dynniq cloud service were implemented with fixed line optical fibre connections and with wireless connection provided by commercial LTE networks.

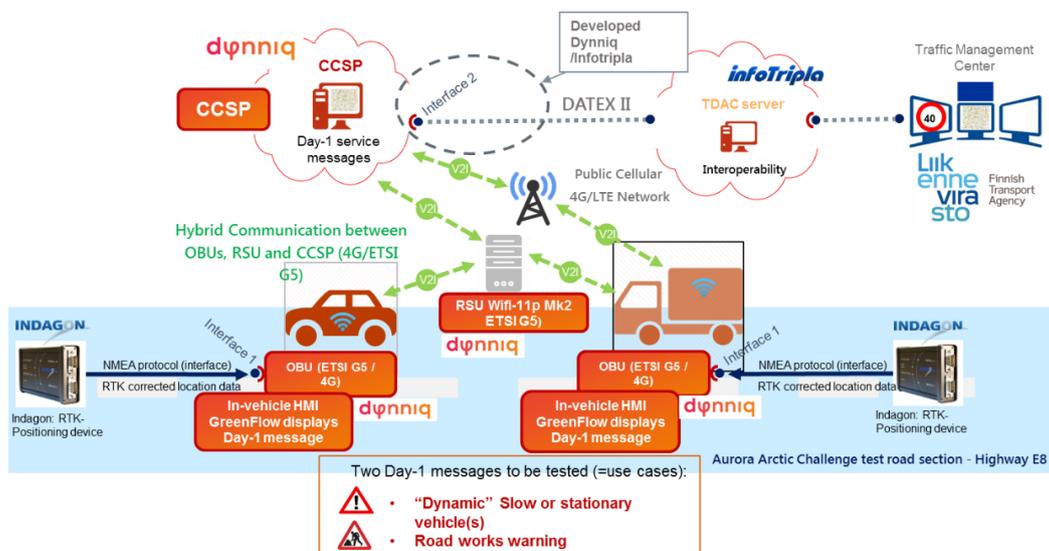


Figure 31. Testfest 2 – test system.

Various combinations of devices, positioning technologies and telecommunications links between the system's components were tested over the course of Testfest 2. The transmission of Day 1 messages was tested using, for example, various types of vehicle to infrastructure (V2I) connections, positioning

technologies (GPS+RTK), antennas, road side units, on-board units and telecommunications links between the RSU and the cloud service. The research team also observed and analysed how changes to configuration affected the system's operation with respect to, for example, message formation and reception, reliable reception of messages and communication latency. All Testfest 2 tests were performed in the Aurora pilot site: the implementation based on the ITS-G5 technology was tested in near Muonio town centre and the LTE implementation was tested in the entire Aurora pilot site (Figure 31).

The Traffic Data Analytics Cloud (TDAC) service used in Testfest 2 was supplied by Infotripla. The TDAC provided the test system with an interface to the national systems that provide real-time traffic information (incl. international interoperability in accordance with the NordicWay1 architecture) and allowed simulated warning messages to be generated. The simulated warning messages formed on the TDAC were communicated to Dynniq's CCSP via which they were transmitted to the vehicle where they were displayed by Dynniq's GreenFlow application. The interface between Dynniq's CCSP and Infotripla's TDAC supported two-way communication which in turn enabled the transmission of stationary vehicle warnings from the CCSP to the TDAC whose implementation in accordance with the NordicWay architecture allowed the international exchange of V2X messages.

Two test vehicles were used in the tests: Indagon's Testlab vehicle and the Snowbox car provided for testing purposes in the Aurora pilot site by the Finnish Transport Infrastructure Agency (FTIA). Both vehicles were equipped with corresponding equipment during Testfest 2:

- OBU (on-board unit, ITS-G5)
- RTK positioning device (Real-Time Kinematics)
- Android tablet (served as the ITS-G5 OBU's user interface)
- Android smart phone (provided a platform for the smart phone application used in the LTE-based implementation)
- PC

In addition to the equipment installed in the test vehicles, the test environment included two C-ITS RSUs and two data cabinets connected to the RSUs and Dynniq's cloud service via an optical fibre connection and wireless LTE connection. One of the data cabinets was equipped with Indagon's RTK positioning base station which was required for accurate positioning in the test area.

The research consortium managed to perform all tests planned for Testfest 2 even though some challenges were encountered over the course of the tests. Solving some of the problems was unexpectedly difficult due to the complexity of the tested system: the test environment consisted of several independent components and telecommunications links between them. Based on the test results, it was concluded that ETSI's ITS-G5 technology is capable of transmitting messages to a distance of approximately 500–800 metres. It was found that the LTE-based implementation enabled more extensive geographical coverage for services providing Day 1 messages. However, in its current state, the LTE based solution was found technologically less mature than the ITS-G5 solution.

Transmission of messages between Infotripla's and Dynniq's systems worked very well during the tests, and the communication latency was very low. Commercial Telia LTE network functioned very well in the test section of the Aurora road, and download speeds from the network to the terminal equipment varied between 11–45 Mbit/s and the upload speeds from the terminal equipment to the network between 17–40 Mbit/s. These values are based on measurements carried out at a single location within the test area and thus, may not be generalisable to the entire Aurora pilot site. The performance of telecommunication company Elisa's commercial LTE network, which was also available within the test area, was slightly lower than that of the Telia network. The private LTE network provided to the test area by Ukkoverkot (Ukko Networks) performed better than the Elisa network but worse than the Telia network.

The Day 1 messages specified by ETSI were found generally useful and appropriate for providing warnings to drivers and vehicles. Nevertheless, there are still some questions to be solved in the future:

- How to define an appropriate range for a warning or a message?
- Where should Day 1 messages be formed?
- To whom should Day 1 messages be communicated?
- How long should different types of Day 1 messages remain active, and what should be the criteria of deactivating a message?
- Which business models could the generation, transmission and reception of Day 1 messages be based on?
- How to avoid sending or presenting an excessive number of messages to a driver?
- What is the best method of presenting messages to a driver?

2.2.4.3 Testfest 3

Testfest 3 was organised in Tampere on 10–14 June 2019. The two first days of Testfest 3 were spent on configuring the tested system and ensuring its operability. The actual tests took place between Wednesday the 12th and Friday the 14th. The test road was equipped with Dynniq's RSU and Indagon's positioning base station (Figure 32). In addition, the test equipment included the automated vehicle Martti and the Testlab vehicle, which were equipped with RTK correction signal equipment (Figure 33).



Figure 32. Dynniq's RSU and Indagon's positioning base station.



Figure 33. Testlab vehicle and automated vehicle Martti in Testfest 3.

Results of the tests carried out on Wednesday 12 June 2019

The first test day started with ensuring that all four Day 1 services were functional. When starting the tests, some problems were observed in the operability of the tested Day 1 services (Table 6):

- The LTE on-board unit connected to the LTE network did not display the stationary vehicle warning received from the CCSP in the correct manner. However, the OBU indicated the location of the event on the map which suggests that it most likely had received the Decentralised Environmental Notification Message (DENM) containing the warning.
- The stationary vehicle warning was not communicated correctly from Dynniq's CCSP to Infotripla's TDAC.
- During the test carried out between 09:30 and 11:00 am, it was observed that the warnings displayed by the LTE OBU were intermittent. The warnings were first initiated, then started to break up and then continued (test drives 10:39–10:42 and 10:57–11:04).

Table 6. The operation of Day 1 services at the start of the first test day of Testfest 3 (display of warnings in the user interface and the relay of the DENM).

Technology	Time of warning (reception by the OBU, comments)			
	Stationary vehicle warning	Reindeer warning	Slippery road warning	Roadworks warning
ITS-G5	10:03	09:37	09:37	09:39 (ITS-G5 OBU displayed the roadworks warning as the "other danger" sign)
LTE (commercial, Telia network)	- (The LTE OBU did not display the warning symbol even though the DENM may have been relayed)	10:20	10:20 (The warning displayed by the LTE OBU kept breaking up)	10:20 (The warning displayed by the LTE OBU kept breaking up)
LTE (private)	- (Connection to the network could not be established with the available equipment)	- (Connection to the network could not be established with the available equipment)	- (Connection to the network could not be established with the available equipment)	- (Connection to the network could not be established with the available equipment)

The problem related to the intermittent display of warnings by the LTE OBUs (slippery road warning, roadworks warning) was fixed by restarting the CCSP server during the lunch break of the first day of testing. SIM cards for the private LTE (pre-5G) network were available, but connection to the network could not be established during the first day of testing. This was probably caused by not having the correct SIM cards for establishing a connection to the network. Consequently, tests could only be carried out using ITS-G5 data transmission and the commercial Telia LTE network during the first two days of testing. Connection to the private 4G network within the test area was established on the last day of testing (14 June 2019) after the correct sim cards were delivered.

During the first day and later when analysing the results, it was observed that Dynniq's CCSP modifies the durations of the warnings relayed by the TDAC. The CCSP added 10 minutes to the duration of the warning which had been sent from the TDAC through the original Datex II interface. As a consequence, warnings of the same type could not be repeated often if the goal was to display the DENM correctly in the user interface.

Results of the tests carried out on Thursday 13 June 2019

On the second day of testing, the tests focused on I2V warnings (roadworks warning, slippery road warning, reindeer warning, Figure 34).

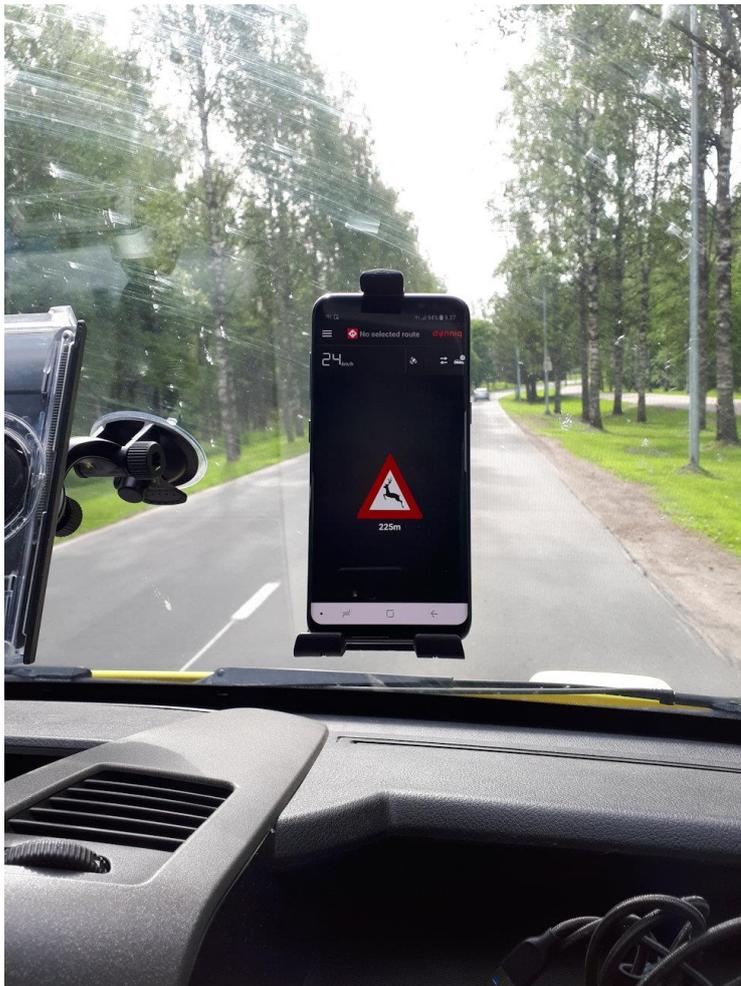


Figure 34. Reindeer warning displayed in the Testlab car.

The tests were carried out with cars that used the ITS-G5 and LTE technologies. The environment for testing I2V messages is illustrated in Figure 35. A summary of the test day's log data is presented in Table 7.

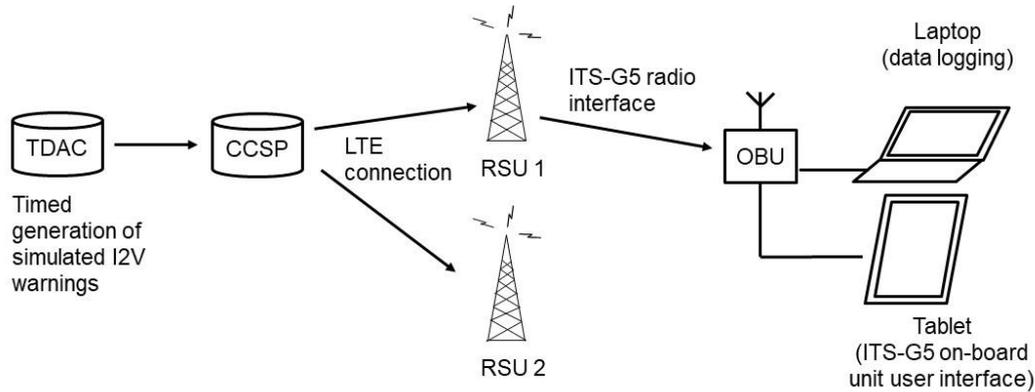


Figure 35. The testing environment used for I2V warnings implemented with ITS-G5 technology.

Table 7. Availability of log files for the second day of Testfest 3 (13 June 2019).

System component	Log data	Time synchronisation
TDAC	Yes	NTP
CCSP	No	-
RSU1	No	-
RSU2	No	-
LTE OBU (Testlab car)	Yes	Probably mobile network time
ITS-G5 OBU (Testlab car)	Yes	GPS

The private LTE network (so-called pre-5G) could not be utilised most likely due to not having the correct SIM cards. Various I2V warnings were sent from the TDAC to the CCSP and from the CCSP to the OBUs in intervals of 20 minutes between 10:00 am and 06:00 pm. The warnings were received with OBUs using the ITS-G5 technology and the commercial LTE network. The results of communications latency measurements carried out with ITS-G5 technology are presented in Table 4.

The data on the reception of DENMs was collected from the ITS-G5 OBU using a laptop. The clock of the laptop used for data collection was not synchronised with a precise time reference during the test. The ITS-G5 OBU, on the other hand, had access to precise time synchronised with the GPS time, but during the test, the internal interfaces of ITS-G5 OBU could not be accessed.

However, the value of the GenerationDeltaTime variable included in the CAMs (cooperative awareness messages) sent by the ITS-G5 OBU during the test could be decoded. The value of the GenerationDeltaTime variable was calculated for

the timestamps provided by the laptop used for data collection in the manner defined in ETSI's specifications. By comparing the aforementioned values of the GenerationDeltaTime variable for the same data packets, it could be established that the laptop's clock was approximately 3.6 seconds behind the OBU's clock and the actual time.

The difference between the OBU's and the data logger laptop's clocks was calculated separately for each DENM and taken into account when calculating the corrected value of latency (Figure 36). The message-specific difference between the clocks was calculated by examining the latest CAM the OBU had sent before receiving the DENM and then comparing the value of the GenerationDeltaTime variable included in the CAM and the timestamp of the same message saved in the log stored on the laptop and the value of the GenerationDeltaTime variable calculated on its basis. The results presented in Table 5 indicate that the time difference between the OBU's and the laptop's clocks varied between 3.528 and 3.669 seconds. This indicates that the calculation method used causes slight inaccuracy in the results concerning latency. However, the error which varies from a few dozen to a maximum of couple of hundred milliseconds is rather small in relation to the latency values that vary from several to dozens of seconds (Table 8)

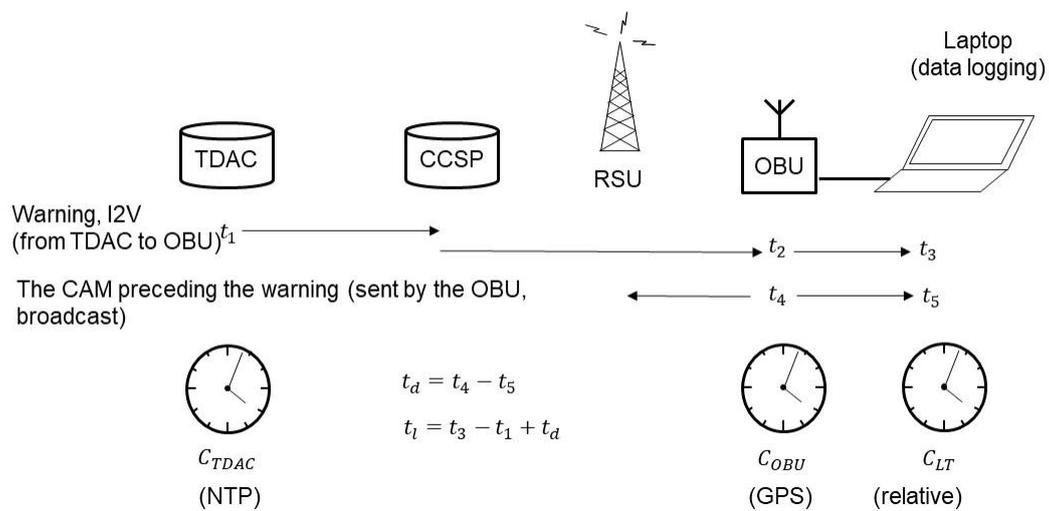


Figure 36. Timestamps used in different components of the system, tested on 13 June 2019, I2V warnings with ITS-G5 technology.

Table 8. Communications latency in I2V applications, message reception by the Testlab car using an ITS-G5 on-board unit, tested on 13 June 2019.

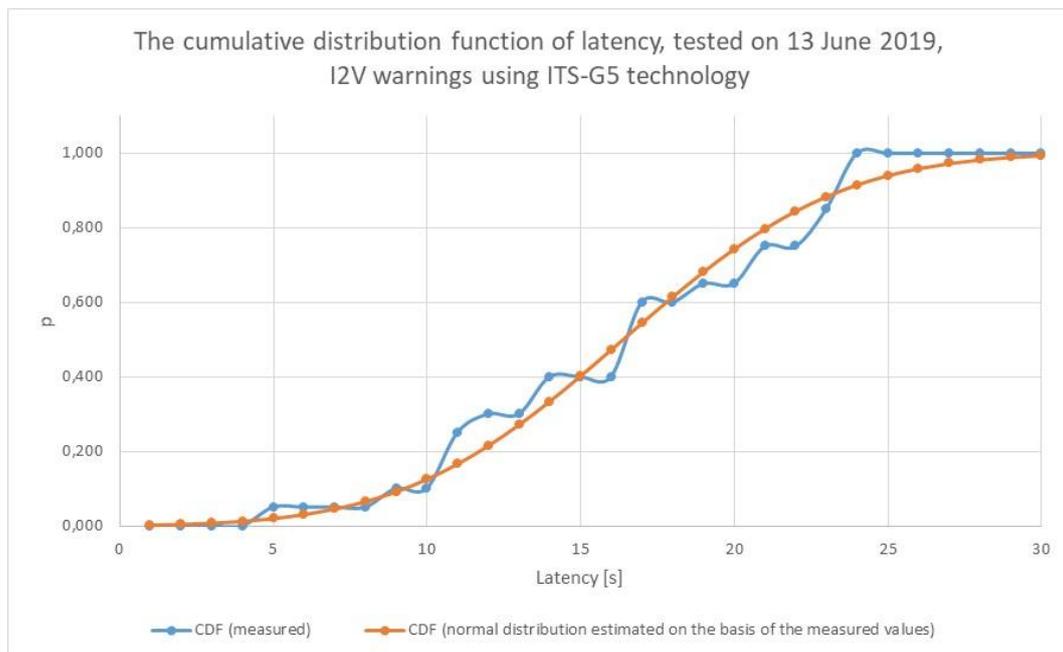
Test run	Activation time (event became visible at TDAC)	T(reception of ethernet frame containing the first DENM, according to laptop timestamp) - T(activation of the event at TDAC) [s]	GenerationDeltaTime [ms] (calculated for the timestamp of ethernet frame provided by laptop used as data logger), for the first CAM message before the DENM	GenerationDeltaTime [ms] (decoded from the CAM message sent by the OBU), for the first CAM message before the DENM	Time difference T(clock: OBU) - T(clock: data logging laptop) [ms]	Message latency [s]
1	10:40	12.631389	60587.180176	64256	3669	16.300
2	11:00	19.647881	63753.810059	1808	3592	23.240
3	11:20	6.923657	29586.939941	33224	3637	10.561
4	11:40	13.131741	14534.060059	18176	3642	16.774
5	12:00	20.131926	18700.769775	22292	3591	23.723
6	12:20	7.131244	25922.949951	29544	3621	10.752
7	13:40	0.770589	35517.209961	39116	3599	4.370
8	14:00	9.821697	64798.270020	2832	3572	13.394
9	14:20	18.818073	28763.439941	32384	3621	22.439
10	14:40	7.834911	38009.690186	41636	3626	11.461
11	15:00	16.872435	22260.109863	25788	3528	20.400
12	15:20	7.267720	12437.579834	16104	3666	10.934
13	15:40	19.289237	44935.950195	48556	3620	22.909
14	16:00	13.299043	59440.040039	63108	3668	16.967
15	16:20	15.288772	16027.719971	19624	3596	18.885
16	16:40	10.279728	31524.940186	35176	3651	13.931
17	17:00	5.301228	46699.430176	50328	3629	8.930
18	17:20	20.790073	17212.289795	20844	3632	24.422
19	17:40	16.799386	33047.239990	36696	3649	20.448
20	18:00	13.336843	50055.869873	53648	3592	16.929

Key statistical indicators were calculated for the results presented in Table 8. Table 9 presents the results of the statistical analysis performed for the latency values presented in Table 8.

Table 9. The statistical indicators of latency, tested on 13 June 2019, the reception of I2V warnings by the Testlab car using ITS-G5 technology.

Statistical analysis	
Minimum	4.370
Maximum	24.422
Mean	16.388
Median	16.852
Standard deviation	5.563
N	20

The cumulative distribution function of the latency of I2V service DENMs (Table 8) and the normal distribution's cumulative distribution function (see Table 9 parameters) were also calculated. The latency distribution received as a test result (Table 8) does not seem to deviate remarkably from the normal distribution corresponding to the material.



The cumulative distribution function of latency, tested on 13 June 2019, I2V warnings using ITS-G5 technology.

Figure 37. The cumulative distribution function of latency and the cumulative distribution function of the normal distribution formed on the basis of the measured latency values (I2V warnings using the ITS-G5 technology, Testlab vehicle).

The I2V warnings were also tested using an implementation based on LTE technology on 13 June 2019. The latency calculation with regard to I2V warnings implemented with LTE technology was complicated by the fact that the LTE OBU did not generate a directly comparable absolute timestamp. The system used for testing the I2V warnings transmitted via LTE network is presented in Figure 38.

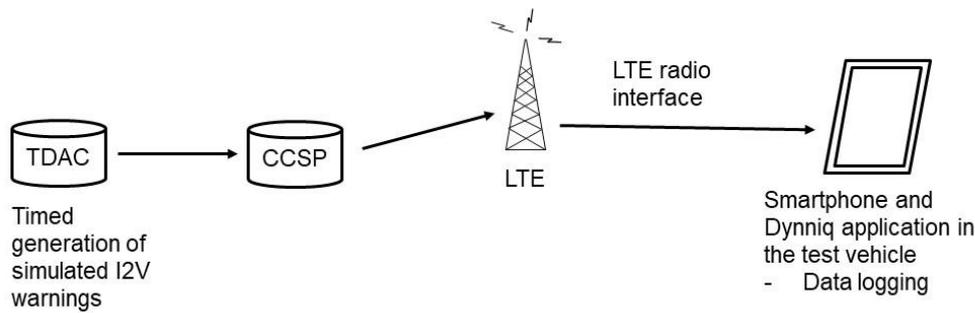


Figure 38. The environment used for testing the I2V warnings relayed to the vehicle using the LTE technology.

The LTE on-board units used in Testfest 3 probably synchronised their clocks with the mobile network time. In Infotripla's TDAC, time synchronisation was realised using the Network Time Protocol (NTP). The CCSP was also most likely synchronised using the NTP. Figure 39 illustrates the timestamps formed at different points of the service chain and time synchronisation of the LTE technology based implementation used for relaying I2V warnings.

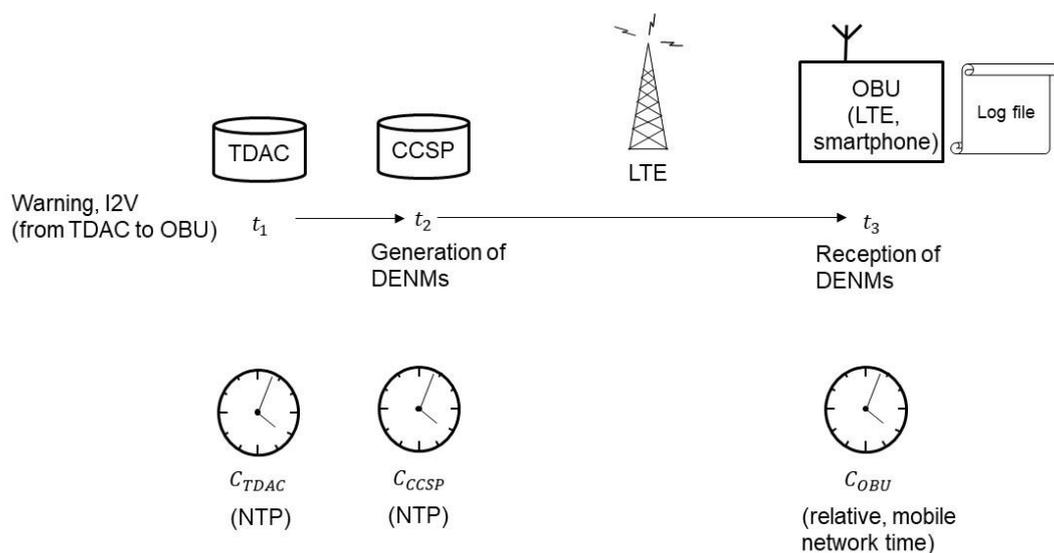


Figure 39. Timestamps and time synchronisation at different points of the service chain, relaying I2V warnings using the implementation based on the LTE network.

The points of time where the TDAC published warnings were known on the basis of the test preparations. The points of time where the CCSP formed the warnings' DENMs were established by examining the log files of the smart phone application receiving the messages. The first DENM corresponding to the warning sent from the TDAC was picked from the log file. The DENM was decoded using an ASN.1 decoder, and the value of the referenceTime variable, which very accurately corresponds to the moment in which the CCSP created the DENM, was looked up from the decoded message. The DENMs sent by the CCSP could not be analysed on the basis of the CCSP's log data because the CCSP system's log data from Thursday 13 June 2019 was not available. The estimated latencies of the I2V warnings when using the LTE implementation are presented in Table 10.

Table 10. Communications latency in I2V applications, message reception by the Testlab vehicle using an LTE on-board unit, tested on 13 June 2019.

Test run	Warning activation at the TDAC server	T(the CCSP formed the DENM in the CCSP) – T(TDAC published the message) [s]	T(OBU received the DENM) – T(the CCSP formed the DENM) [s]	T(the OBU received the DENM) – T(TDAC published the message) [s]
1	10:40	16.354	-3.554	12.097
2	11:00	23.354	-3.392	19.259
3	11:20	10.354	-2.981	6.670
4	11:40	16.855	-3.621	12.532
5	12:00	23.854	-3.352	19.799
6	12:20	10.853	-3.080	7.070
7	13:40	4.598	-2.849	1.046
8	14:00	13.604	-3.329	9.573
9	14:20	22.602	-3.798	18.103
10	14:40	11.618	-3.032	7.883
11	15:00	20.602	-2.598	17.301
12	15:20	11.100	-3.328	7.069
13	15:40	23.118	-3.648	18.767
14	16:00	17.142	-3.618	12.821
15	16:20	19.122	-2.042	16.378
16	16:40	14.116	-2.941	10.472
17	17:00	9.142	-2.644	5.797
18	17:20	24.622	-3.530	20.389
19	17:40	20.642	-2.392	17.547
20	18:00	18.823	-0.570	17.550
Timestamp source	Notes on the TDAC's operation	DENM formation: DENM saved in the OBU's log, referenceTime variable in the decoded DENM Message publication: Notes on the TDAC's operation	DENM reception: LTE OBU's log file DENM formation: DENM saved in the OBU's log, referenceTime variable in the decoded DENM	DENM reception: LTE OBU's log file Message publication: Notes on the TDAC's operation
Time synchronisation	NTP	TDAC: NTP CCSP: NTP	CCSP: NTP OBU: mobile network	TDAC: NTP OBU: mobile network

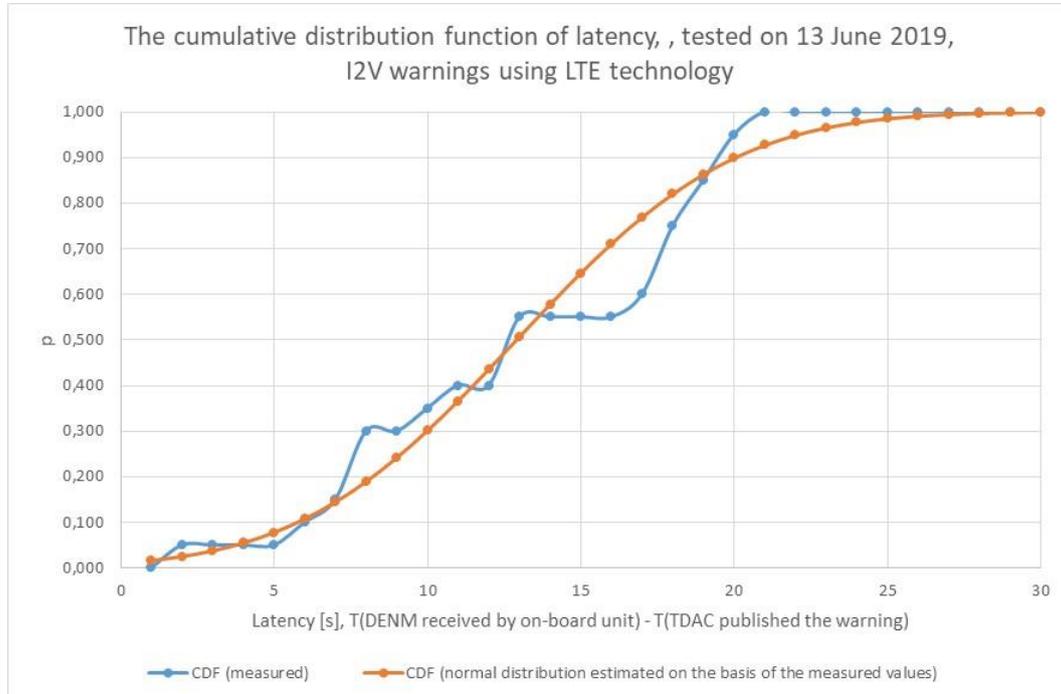
The values in column 4 of Table 10 are logically impossible. There are three possible explanations for them: (1) the clock of the LTE on-board unit has been set at an inaccurate time during the test, or (2) the clock of the CCSP that formed the messages was not synchronised during the test, or (3) the timestamp referenceTime included in the DENMs received by the LTE OBU was set incorrectly for some reason.

In the light of the results of the third day of Testfest 3 (14 June 2019), it seems most likely that the timestamps referenceTime and detectionTime included in the DENM messages were inaccurate for some reason. Therefore, it was justifiable to perform a statistical analysis only for the results presented in column 5 of the table above. Key statistical indicators (Table 11) were calculated for the recorded latency values (I2V warnings, technology based on LTE).

Table 11. Key statistical indicators of latency, tested on 13 June 2019, the reception of I2V warnings by the Testlab vehicle using an LTE on-board unit (the latency from message publication at the TDAC to the reception of the DENM by the OBU).

Statistical indicators T(DENM received by the OBU) – T(TDAC published the message)	
Minimum [s]	1.046
Maximum [s]	20.389
Medium [s]	12.906
Median [s]	12.677
Standard deviation [s]	5.572
N	20

Figure 40 illustrates the distribution of the latency values presented in column 5 of Table 7.



Latency [s] T(DENM received by the OBU) – T(TDAC published the message)

Figure 40. The cumulative distribution function of latency and the cumulative distribution function of the normal distribution formed on the basis of the measured values of latency (I2V warnings using the LTE technology, Testlab vehicle).

Results of the tests carried out on Friday 14 June 2019

The tests carried out on Friday the 14th focused on V2V messages communicated from one test vehicle to another. In practice, the tests focused on communicating the stationary vehicle warning from one test vehicle to another using ETSI ITS-G5 and LTE technologies. The test environment is illustrated in Figure 41. A summary of the log files available for the test day is presented in Table 12.

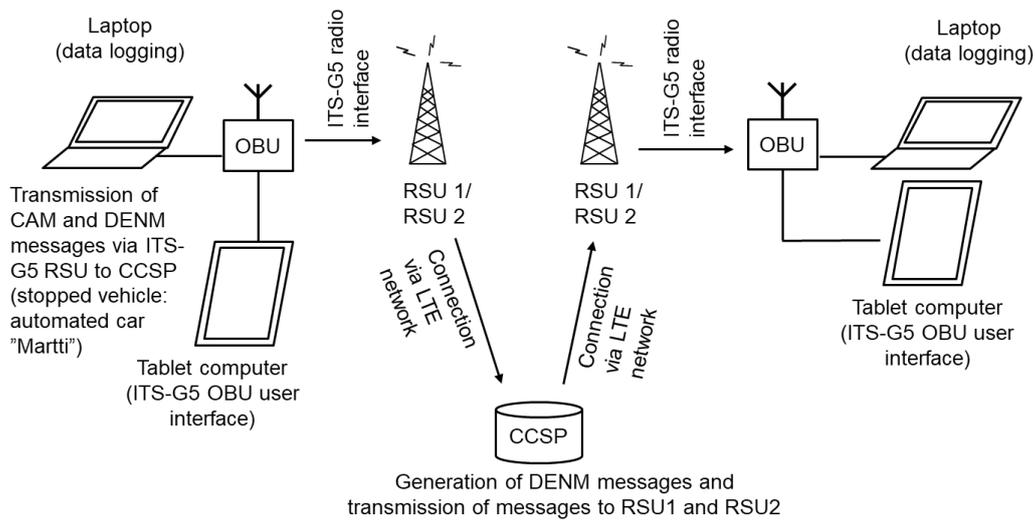


Figure 41. The environment for testing V2V warnings implemented with ITS-G5 technology.

Table 12. Log files of the third day of Testfest 3 (14 June 2019).

System component	Log data	Time synchronisation
TDAC	Yes	NTP
CCSP and other components of Dynniq's system	No	Probably NTP
RSU1	No	-
RSU2	No	-
LTE OBU (Testlab car)	Yes	Mobile network or GPS time
ITS-G5 OBU (Testlab car)	Yes	GPS
ITS-G5 OBU (Martti)	Yes	GPS

Figure 42 presents the timestamps used in the different components of the test system.

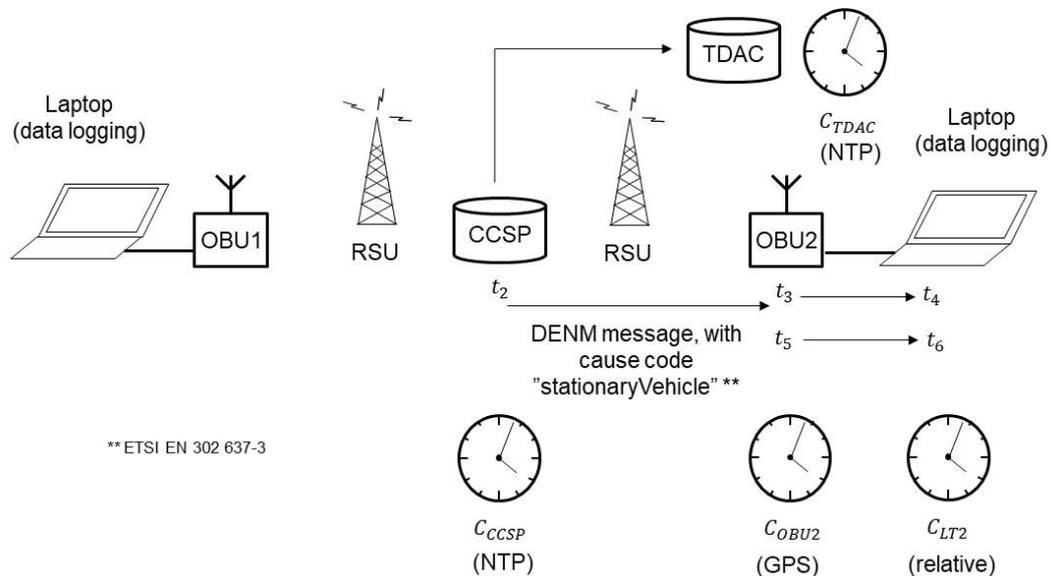


Figure 42. Timestamps and time synchronisation at different points of the service chain, transmission of V2V warnings using the implementation based on the ITS-G5 technology.

When analysing the log data of the third day of Testfest 3, the aim was to first pinpoint the accurate timestamp for the moment where the examined event began. In practice, this means the moment where the system detected that the automated vehicle Martti stopped close to the bus stop at the crossroads of Ahvenisjärventie Street and Lindforsinkatu Street.

The aim was to first identify the moment of stopping based on the log data of the automated vehicle Martti's ITS-G5 on-board unit. However, for some reason, CAMs corresponding to the stops that took place in the test area at specified points of time could not be found in the log data of the OBU placed in the vehicle on 14 June 2019 even though the ITS-G5 OBU most likely sent them, or at least it should have as it operated in accordance with the standards. Therefore, the log data of the test vehicle Martti's ITS G5 OBU could not be utilised when determining the point of time where the event that triggered the tested Day 1 message (stationary vehicle) took place. The test team attempted to determine the start time of the event based on the log files of the CCSP used for generating the DENM messages. However, this proved practically impossible as the CCSP server's log data had disappeared after the test.

After this, the test team tried to determine the point of time where the test vehicle Martti had stopped on the basis of the log data collected in the Testlab car that included the messages received during the day. From the OBUs placed in the Testlab car (ITS-G5, LTE and pre-5G), the team managed to decode the timestamp for the formation or the most recent update of the stationary vehicle warning (DENM) and for identifying the event (stationary vehicle). The aforementioned timestamps decoded from the DENM correspond to the variables referenceTime and detectionTime of specification EN 302 637-3. These timestamps were first rendered into unixtime timestamps, after which they were rendered into a readable format that could be examined by the user.

In addition to the event's start time, it was necessary to determine the point of time where the Testlab car's OBU had received the stationary vehicle warning. The timestamps of the LTE and pre-5G OBUs could be read directly from the log file generated by the unit. Determining the timestamp of the ITS-G5 OBU was more complex as a separate laptop was used for collecting the data, and the laptop did not provide an accurate timestamp. However, the ITS-G5 OBU used GPS, and it sent CAMs that specified its location and contained a partial timestamp containing the last five digits of an absolute timestamp (GenerationDelta-Time variable, see ETSI EN 302 637-2). The difference between the timestamp of the CAM generated by the ITS-G5 and the timestamp specifying the point of time where the laptop sent the package could be calculated. This calculation enabled determining an exact point of time for other messages received and sent by the ITS-G5 OBU.

The results of the third day of testing, 14 June 2019, are compiled in Tables 13–15.

Table 13. Results on communications latency in V2X applications, message reception by the Testlab vehicle using an LTE on-board unit, tested on 14/06/2019.

Test run	Test performance start time (approx.)	DENM (actionID, sequence number)	Event detected (the "detectiontime" variable of the received DENM)	Message reception in the TDAC	Message reception by the test vehicle, LTE OBU
1	11:00	46-553	11:02:38.614	11:02:33.428	11:02:38.704
2	11:20	46-559	11:22:58.045	11:22:54.422	11:22:54.234
3	11:40	46-563	11:42:44.623	11:42:40.929	11:42:40.830
4	12:00	46-570	12:02:54.750	12:02:50.914	12:02:51.089
5	13:50	46-604	13:52:35.604	13:52:31.935	13:52:31.873
6	14:10	46-608	14:12:40.584	14:12:36.918	14:12:37.183
7	14:30	46-612	14:32:21.600	14:32:17.927	14:32:17.728
8	14:50	46-616	14:52:50.144	14:52:46.443	14:52:46.119
9	15:09	46-620	15:12:15.095	15:12:11.414	15:12:11.425
10	15:30	46-626	15:32:28.139	15:32:24.42	15:32:24.570
11	15:50	46-632	15:52:16.765	15:52:12.931	15:52:13.375
12	16:10	46-641	16:12:12.633	16:12:08.932	16:12:13.540
13	16:30	46-653	16:32:16.621	16:32:12.95	16:32:12.749
14	16:50	46-667	16:52:09.076	16:52:05.46	16:52:14.791
15	17:10	46-676	17:12:05.641	17:12:01.956	17:12:02.018

Test run	Test performance start time (approx.)	DENM (actionID, sequence number)	Event detected (the "detectiontime" variable of the received DENM)	Message reception in the TDAC	Message reception by the test vehicle, LTE OBU
Timestamp source	Notes made during the test		LTE OBU log file, DENM variable "detectiontime" set in Dynniq's system	TDAC log file	LTE OBU log file
Time synchronisation	Probably the mobile network time		Unknown	TDAC: NTP	OBU: probably the mobile network time

Table 14. Results on communications latency in V2X applications, message reception by the Testlab car using a pre-5G on-board unit, tested on 14/06/2019.

Test run	Test performance start time (approx.)	DENM (actionID, sequence number)	Event detected (the "detectiontime" variable of the received DENM)	Message reception in the TDAC	Message reception by the test vehicle, pre-5G OBU
12	16:10	46-641	16:12:12.633	16:12:08.932	16:12:13.955
13	16:30	46-653	16:32:16.621	16:32:12.95	16:32:13.094
14	16:50	46-667	16:52:09.076	16:52:05.46	16:52:15.290
15	17:10	46-676	17:12:05.641	17:12:01.956	17:12:02.287
Timestamp source	Notes made during the test		Pre-5G OBU log file, DENM variable "detectiontime" set in Dynniq's system	TDAC log file	Pre-5G OBU log file
Time synchronisation	Probably the mobile network time		Unknown	TDAC: NTP	OBU: probably the mobile network time

Table 15. Results on communications latency in V2X applications, message reception by the Testlab vehicle using an ITS-G5 on-board unit, tested on 14/06/2019.

Test run	Test performance start time (approx.)	DENM (actionID, sequence number)	Event detected (the "detection-time" variable of the received DENM)	Message reception in the TDAC	Message reception by the test vehicle, ITS-G5 OBU
1	11:00	46-553	11:02:38.614	11:02:33.428	11:02:38.864
2	11:20	46-559	11:22:58.045	11:22:54.422	11:22:59.836
3	11:40	46-563	11:42:44.623	11:42:40.929	11:42:46.358
4	12:00	46-570	12:02:54.750	12:02:50.914	12:02:56.537
5	13:50	46-604	13:52:35.604	13:52:31.935	13:52:37.344
6	14:10	46-608	14:12:40.584	14:12:36.918	14:12:42.941
7	14:30	46-612	14:32:21.600	14:32:17.927	14:32:23.442
8	14:50	46-616	14:52:50.144	14:52:46.443	14:52:51.856
9	15:09	46-620	15:12:15.095	15:12:11.414	15:12:16.835
10	15:30	46-626	15:32:28.139	15:32:24.42	15:32:29.922
11	15:50	46-632	15:52:16.765	15:52:12.931	15:52:18.710
12	16:10	46-641	16:12:12.633	16:12:08.932	16:12:14.368
13	16:30	46-653	16:32:16.621	16:32:12.95	16:32:18.360
14	16:50	46-667	16:52:09.076	16:52:05.46	16:52:15.730
15	17:10	46-676	17:12:05.641	17:12:01.956	17:12:07.426
Timestamp source	Notes made during the test		LTE OBU log file, DENM variable "detectiontime" set in Dynniq's system	TDAC log file	Log file of the laptop used for data collection
Time synchronisation	Probably the mobile network time		Unknown	TDAC: NTP	OBU: probably the mobile network time

The latency of the V2X stationary vehicle warning tested on the third day of testing cannot be calculated directly on the basis of Tables 13–15 because the exact points of time of detecting the stationary vehicle or stopping the vehicle are not known. However, it is possible to examine approximately the duration of the time period in which the same message was received at the TDAC and the OBUs used in the test (Table 16). The results are marked by a certain degree of uncertainty as it was not possible to synchronise the clocks of the LTE or pre-5G

OBUs with a single time reference, and the timestamps of these units are most likely based on the mobile network time. The timestamps of the ITS-G5 OBU could be connected to the partial timestamp decoded from the CAMs sent by the OBU. Thus, it is likely that the data concerning the ITS-G5 OBU is more accurate than the data concerning the LTE or pre-5G OBUs. The data of Table 16 suggests that the ITS-G5, LTE and pre-5G OBUs received the same warning within a time period of a few seconds in the 15 test runs performed on 14 June 2019.

Table 16. The time of receiving the warning in relation to the reception of the warning in the TDAC

Test run	Test performance start time (approx.)	T + warning reception in the TDAC [s]		
		ITS-G5 OBU	LTE OBU	Pre-5G OBU
1	11:00	5.436	5.276	-
2	11:20	5.414	-0.188	-
3	11:40	5.429	-0.099	-
4	12:00	5.623	0.175	-
5	13:50	5.409	-0.062	-
6	14:10	6.023	0.265	-
7	14:30	5.515	-0.199	-
8	14:50	5.413	-0.324	-
9	15:09	5.421	0.011	-
10	15:30	5.502	0.15	-
11	15:50	5.779	0.444	-
12	16:10	5.436	4.608	1.024
13	16:30	5.41	-0.201	4.162
14	16:50	10.27	9.331	2.34
15	17:10	5.47	0.062	-3.173

2.2.5 Evaluation of results

Testfest 1 and Testfest 2

Testfests 1 and 2 focused on ensuring the basic functionality of the technological solutions used for transmission of Day 1 messages. Dissemination of two Day 1 messages (stationary vehicle warning and roadworks warning) using solutions based on the ITS-G5 and LTE technologies was successfully verified and demonstrated in the first two Testfests. The tests also provided information on technical functioning of the solutions developed for communicating Day 1 messages, cross-border international interoperability of the messages and technical functioning of accurate RTK positioning under arctic conditions.

Testfest 3

Testfest 3 could not be implemented in March 2019 in accordance with the original plan because the software version required for the tests was not completed until the second week of June 2019. However, the date of Testfest 3 could not be moved to the week that started on 17 June or another later date due to problems related to the summer holiday period and coordinating the stakeholders' schedules. The time period between the completion of the software version required for Testfest 3 and the planned starting date of the tests was relatively short, and most of it had to be spent on ensuring the operability of the test system's basic functionalities and verifying the data logging capabilities of the system. The amount of available time and resources did not enable testing the collection and analysis of the log files in order to practice the test situation prior to performing the tests of Testfest 3. On its part, this hindered securing functional data collection and ensuring the usability of the data. Analysing the log data collected in Testfest 3 was a more laborious and complex task than planned largely due to the aforementioned reasons. Furthermore, the CCSP log data generated during the last two days of Testfest 3 (13–14 June 2019) was lost. Thus, this log data could not be used for verifying the results of Testfest 3 which adds to the uncertainty of the results.

The system tested in testfest 3 had basic documentation which allowed the tests to be carried out. However, the system had also non-documented features which were encountered during the tests, and this slowed the implementation of the tests to some extent. On the first day of Testfest 3 (12 June 2019), it was observed that the CCSP server sets a minimum value of 600 seconds for the variable ValidityDuration in all DENMs it sends regardless of the event's (e.g. slippery road warning or another warning) duration set by the server sending the warning (TDAC in Testfest 3). As a consequence, the test team had to wait for at least 600 seconds (10 minutes) after the initiation of each warning for the CCSP to return to its initial state. As the DENMs had to be decoded and the log data analysed manually without automated tools, it was practically impossible to analyse any material containing several simultaneously active warnings.

In addition, the communications latency measured during Testfest 3 was likely affected by the applied test system parameters which had also been used in the implementation of the test systems prior to the tests. For example, warnings were retrieved from the TDAC to the CCSP in predefined intervals instead of event-driven retrieval. It should be possible to further reduce the latency by modifying the intervals in which new messages are retrieved from one system component to another.

Due to the limitations of the test system, all of the system's components could not be synchronised with a single time reference during Testfest 3. Thus, it is justifiable to re-perform the tests on communications latency after gaining access to a system that enables accurate synchronisation of the system components' clocks.

2.3 Vehicle remote control and communication infrastructure

Ensuring the safety of autonomous driving in Arctic conditions might be challenging unless border cases are handled with remote human assistance. Due to this issue, a remote control method was tested in vt21 conditions. In concept the remote operator can make a direct teleoperation connection to the autonomous vehicle in order to solve the safety critical situation.

In the method the tests were performed using a commercial LTE network. To evaluate the connectivity of the host vehicle, there are two main communication routes that need to be analysed, i.e. (i) the connection between the host vehicle to the base transceiver station (BTS), and (ii) the connection between a remote-control station to the host vehicle.

In the Arctic Challenge project, the Sod5G test track serves as a reference test environment especially for 5G communication, as it possesses an active 5G test network and advanced road weather stations, linearly with an expected final configuration of the primary Arctic Challenge testing site at the Aurora open road-testing area in Muonio.

In certain scenarios, independent obstacle avoidance by the host autonomous vehicle is not possible. This is due to several possibilities, such as the requirement of complex path planning solutions, among many others. Thus, to overcome this, a remote control solution is desirable to provide assistance to collision mitigation issues. This involves the overriding of the input from the high-level module to the autonomous vehicle low-level control by a remote operator.

Table 17. KPIs for 4G / LTE network used in the study.

KPI	Target Value
Latency	under 100 ms
Bandwidth	over 5 mbs
Packet loss	0 %

Table 18. KPIs of 5G test network measurements.

Key Performance Indicators	Description of KPI	Threshold values
5G test network overall Linear performance	Jitter presents average packet delay; therefore estimated threshold jitter (Cisco) value is expected to balance the operation	30 ms
5 G test network average throughput	Average throughput is a good KPI for analysing the performance of the 5G test network by comparing it with a threshold value	5 Mbps
5G test network Service availability on Test track	Service availability is another good KPI by analysing the availability of network coverage on the FMI test track	90 % service availability during each lap

2.3.1 4G/LTE Network LTE

To verify the utilised LTE network in the remote control experiment, the AV was driven at varying speeds (30, 50 and 80 km/h) in the vt21 main test area near Muonio. The analysis includes the throughput, packet loss and the delay. The post-analysis summary of the results is shown as follows. The ping analysis summary for the cases was done using offline network analysis software and the summary is denoted below (Table 19).

Table 19. Ping analysis summary.

Measurement	Displayed
Packets	2588 (100.0%)
Time span, s	858.981
Average pps	3.0
Average packet size, B	260.5
Bytes	675114 (100.0%)
Average bytes/s	785
Average bits/s	6287

For this connection route, the summary is as follows, together with its round-trip time (RTT) in Table 20.

Table 20. Analysis of the Network Latency Test.

Average packets per seconds	3.0
Type of Connection	4G
RTT Min (ms)	30.621
RTT Average (ms)	47.485
RTT Max (ms)	168.071
RTT MDev (ms)	9.806
Packet Loss Percentage (%)	0

Following the results above, with 0% packet loss and a min value of the round-trip time of 30.621 ms, the utilised network is seen to abide to the network KPI listed in the experimental set-up for 4G. Thus, usage of 4G is expected to enable the RC operation with several limitations coming from bandwidth (video streaming, for example).

2.3.2 5G test network measurements for reference

The results of seven continuous measurement drives at constant speed are presented below in Table 21.

Table 21. Key performance indicators performance evaluation.

KPI Numbers	Key Performance Indicators	Description of KPI	Threshold values	Test results
01	5G test network overall Linear Performance	Jitter presents average packet delay; therefore, estimated threshold jitter value (Cisco) is expected to balance the operation.	30 ms	5.20 ms
02	5 G test Network average throughput	Average throughput is a good KPI to analyze the performance of the 5G tess network by comparing it with a threshold value	5 Mbps	2.4 Mbps
03	5G test network Service availability on test track	Service availability is another good KPI for analysing the availability of network coverage on the FMI test track	90 % service availability during each lap.	88 %

In order to analyse network performance, productivity and efficiency, we need to consider KPIs for comparison with our pilot measurements. It would make it easy to develop network management and establish network chunks with all the desirable capabilities within the overall 3GPP and IEEE 802.11p infrastructure. According to Table 21, the 5G test network performance is acceptable after comparing it with the threshold value because the measurement jitter value is less than the threshold. It can also be seen that the average throughput of the 5G test network is acceptable after comparing it with a threshold value (Mbps), and there is a slightly low throughput in the test measurements. This might be because of lost packets, jitter and overall network coverage.

The other issue in analysing the performance of pilot measurements is to check service availability during test drives. It is obvious in test use cases that with limited resources the 5G test network will be the emerging technology in the next few years, and it will have a huge impact on vehicular communication. A real 5G network will focus on very high data rates with very low latency, praiseworthy user experiences in densely populated areas, vehicular communication, proficient management of several devices, and reliability.

2.3.3 Remote control obstacle avoidance test

For the remote control application, the results are discussed following the previous discussion regarding the network latency test. Figure 43 illustrates the experimental results, where the host vehicle navigated on the predefined trajectory autonomously (green line) when a previously unknown obstacle (yellow) appears in the trajectory. When the safety threshold is violated and it is impossible for the vehicle to take over, the vehicle stopped. The avoidance manoeuvre performed by the remote operator is shown in red, where the remote operator avoided the obstacle and led the vehicle back to its original trajectory, allowing for the vehicle to return to autonomous driving mode again. As can be seen, the second obstacle appeared (purple), and the takeover is done by the remote operator in the same manner as previously stated.

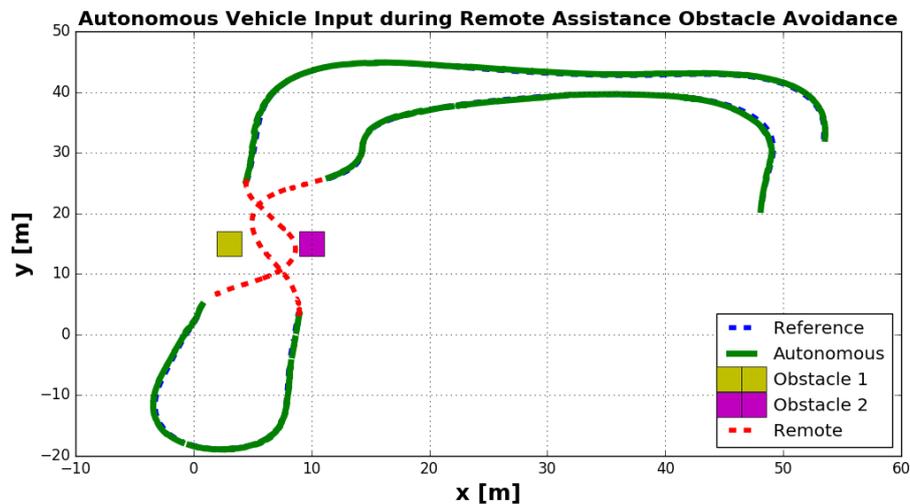


Figure 43. Input to the Autonomous Vehicle low-level controller during the testing session.

Figure 44 shows obstacles in blue, which is sent to the remote control room for the remote operator's monitoring purpose. Once the safe threshold is violated, the remote operator handled the takeover based on the information received.

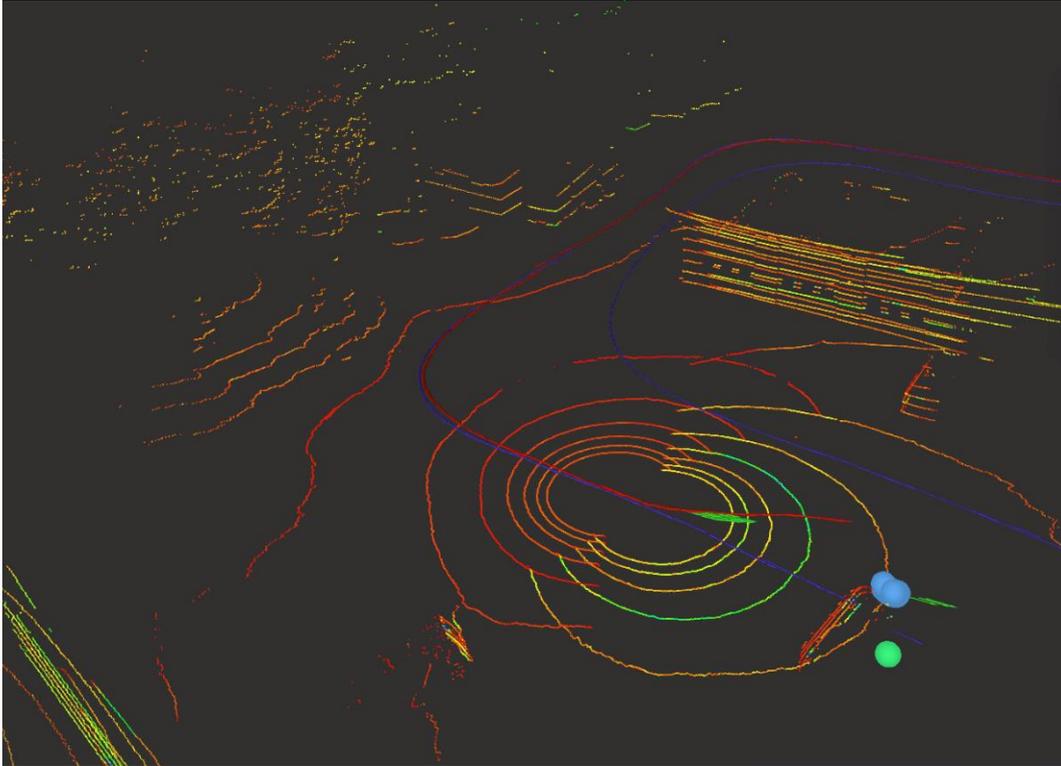


Figure 44. The obstacle existence.

The information on the vehicle's perception module and environment is sent to the remote operator over the network, allowing for continuous monitoring of the host vehicle states throughout the navigation. As can be seen, once the obstacle has been avoided, the remote operator enables the autonomous mode again by guiding the vehicle towards the nearest point in the predefined trajectory.

Despite the obstacle avoidance having been successfully performed, in Figure 45 a delay in data streaming (live video feed) from the AV to the remote control is evident, where the video is still not showing the obstacle in the remote operator's screen (camera view on the right), while in reality, the host vehicle's view is currently showing the image of an obstacle in front of the AV, i.e. the van (left camera image). This means there is a requirement for a faster connection.

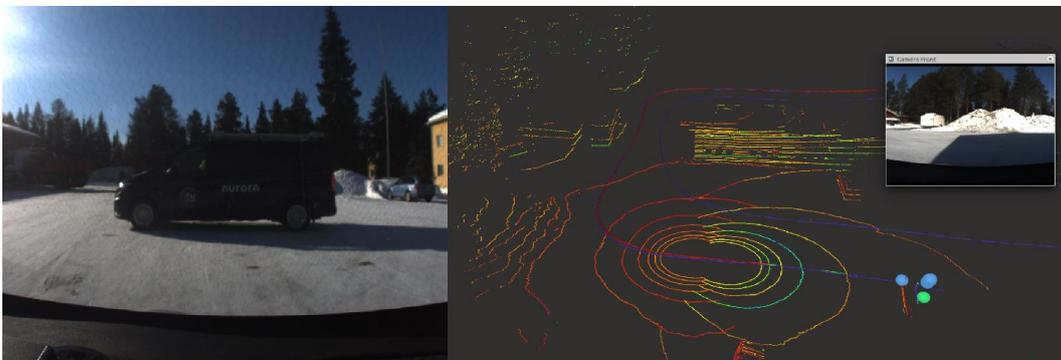


Figure 45. Real-time image streaming comparisons, where the operator's view is seen in the right figure while the real-time environment is shown in the left figure.

2.4 Vehicle positioning

Positioning is one of the main prerequisites for autonomous driving. Safe driving requires that the vehicle knows its position at all times with high accuracy. Typically, the requirement is that transverse accuracy should remain within 5–10 cm. GNSS is often used as one method to support positioning. However, by itself the technology is prone to suffer from loss of signal and hence accuracy, especially in the north and in urban areas where the visibility of satellites might be limited. In the Arctic Challenge project, several approaches based on sensor fusion were tested using inertia, RTK-GNSS, SLAM and HD maps.

To be able to analyse the performance of our positioning system, a reliable "ground truth" is required. In this case, an RTK-GNSS receiver was used as a "ground truth". However, it was first necessary to test how good the GNSS reception is on the road itself so the "ground truth" quality can be estimated. This comprises several preliminary validations.

The ComNav T300 (ComNav, 2019) was the RTK system that was chosen since it fulfils the technical requirements and was the most affordable RTK system we surveyed. It can track all the working GNSS constellations (GPS, Glonass, Beidou, Galileo and IRNSS).

Therefore, the major techniques for localising an autonomous car are based on SLAM and HD maps. SLAM compared consecutive point clouds derived from the autonomous car to find the orientations and positional changes of the moving car. Such point clouds can be obtained from LiDAR, time-of-flight camera, i.e. flash LiDAR or stereo camera.

Table 22. KPIs for positioning.

KPI	Target Value
MSE X axis error	under 0.1
MSE Y axis error	under 0.1
Average error (m)	under 0.25
Weather effect on accuracy	less than 10%

2.4.1 GNSS positioning

GNSS Reliability Analysis

It is good to remember that GNSS positioning at higher latitudes is difficult due to the poor availability of satellites and unfavourable geometric distribution. Few satellites are along the route and not many reach a high enough elevation for transmitting a good quality signal.

GNSS Dataset from December 14th of 2017

Juto was used as the test platform and data gathering system, and it used the FGI local correction signal to get the RTK corrections. Finally, the GNSS receiver was the Comnav T300. Ninety-nine percent of the trajectory had a FullRTK fix for GNSS positioning, meaning that the highest level of precision was achieved for the GNSS solution computation. Also, the availability of satellites can be summarised as below:

Satellites availability

- min 11
- max 19
- average 16.686

GNSS dataset from 9 April 2018

In this dataset the exact same experiment was performed as in the previous section, with the only difference being the season. About 95% of the trajectory had a FullRTK fix for the GNSS positioning, meaning that the highest level of precision was achieved for the GNSS solution computation. However, in this dataset there was a moment in time when there was no available Fix. Satellite availability is summarised below:

Satellites availability

- min 0
- max 28.671
- average 20.921

The above numbers indicate an overall better satellite availability along the road compared with the dataset presented in the previous section. However, it also indicates that at some point in the road there was no available fix for the positioning using GNSS.

2.4.2 HD maps (SolidPotato approach)

Autonomous SLAM

Autonomous SLAM positioning accuracy was investigated by comparing the SLAM-derived trajectories from individual test runs against the high-quality reference trajectory, having an estimated accuracy of 2–5 cm.

Results show that at long distances the drift in SLAM positioning can be up to 6–7% of the travelled distance, e.g. an error of about 600 metres on a 9 km-long test run. Figure 46 gives an overview of the errors in individual SLAM trajectories compared to the reference trajectory. Thus, the SLAM correction is comparable to the use of IMU (Inertial Measurement Unit), which corrects the relative positioning of the car. Higher accuracy in relative positioning can be obtained by merging SLAM and IMU data. Also, using higher quality lidar, the integrated use of a number of lidars together, and the use of high-quality IMU improve the relative positioning of the autonomous car. However, they do not solve the problem related to the absolute positioning of the car. The frequency of the absolute positioning needed is based on the quality of the SLAM and IMU integration applied in the autonomous car.

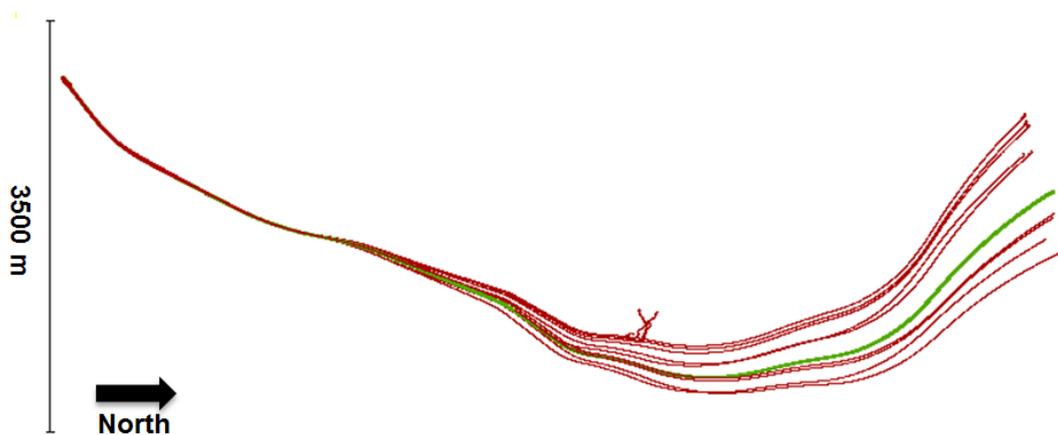


Figure 46. SLAM trajectories (red) and reference trajectory (green) on a 9 km long Aurora test environment.

Trajectories are matched together at the south end of the route (left side in figure) and the total amount of SLAM drift can be seen at the north end (right side).

This result confirms the need to use high-definition maps (HD maps) in the absolute localisation of the car. Instead of matching consecutive lidar data with each other to produce the relative localisation (SLAM), absolute localisation is performed to match lidar data with reference lidar data (HD map) having an absolute position. There can be various ways of combining SLAM and HD map approaches. The road environment, i.e. what kinds of features are available at the scene, affects the accuracy of matching, as can be seen in the following section. These topics were studied by Zhang et al (Zhang, 2014).

Laser scanning data and HD map

The accuracy of vehicle location with the use of vehicle-based laser scanning data and an HD point cloud map was analysed by dividing point cloud data, collected with a VLP-16 laser scanner, into five-second segments and measuring how accurately these segments can be matched with the HD point cloud map. During the five-second segment, internal orientations are corrected with the SLAM. This, however, causes some errors, which can be seen as bias or absolute localisation error. An example of the data sets is shown in Figure 47. The correlation between vehicle-derived laser scanning data and reference point cloud is weaker when conditions change. The changes are the strongest between comparisons carried out between winter and summer. Snow coverage in particular deteriorates the correlations. It is assumed that areas where snow is packed into snowbanks are the most difficult cases.

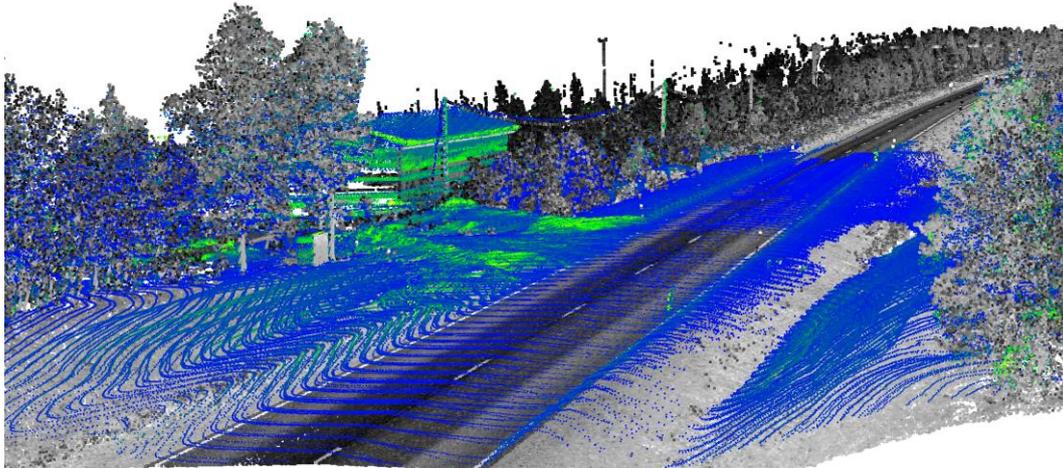


Figure 47. Example of summertime HD point cloud map (greytones) and one 5 second segment of wintertime VLP-16 data (green-blue colours).

Both wintertime and summertime reference HD point clouds were used for evaluating the location accuracy using the 5 s segments collected in January (subsequent days for ROAMER and VLP-16 data collections) and April. Analysis was divided to cover five typical scenes along the Aurora road into categories of open road crossings, residential areas, rock cuts, tall forest and small forest. The pointcloud-to-pointcloud distances (location difference between the pointclouds after pointcloud matching) are shown in Table 23. Thus, the errors are the systematic errors between the pointclouds. These errors can be diminished using a shorter updating time (5 s), using IMU and SLAM integration and so on. The selected values are things such as error upper bounds, since localisation of the vehicle is needed in operative autonomous driving roughly 10 times per second.

Table 23. Pointcloud-to-pointcloud distances after matching the VLP-16 segments to refer-ence data.

Scene	Pointclouds		Point distances std	
	Ref.data	VLP-16	XY [m]	Z [m]
Road crossings	Summer	January	0.53	0.35
	Summer	April	0.49	0.33
	January	January	0.52	0.24
	January	April	0.34	0.24
Residential	Summer	January	0.29	0.31

Scene	Pointclouds		Point distances std	
	Ref.data	VLP-16	XY [m]	Z [m]
	Summer	April	0.25	0.34
	January	January	0.32	0.20
	January	April	0.27	0.22
Rock cut	Summer	January	0.14	0.24
	Summer	April	0.16	0.25
	January	January	0.05	0.04
	January	April	0.08	0.11
Tall forest	Summer	January	0.19	0.24
	Summer	April	0.15	0.26
	January	January	0.17	0.12
	January	April	0.22	0.21
Small forest	Summer	January	0.18	0.19
	Summer	April	0.16	0.19
	January	January	0.19	0.13
	January	April	0.17	0.14

When data from different seasons is compared, results show that laser data can only yield better accuracy in an environment with distinct features (rock cut and forest), but a lower amount of and longer distances to features limit the accuracy in built-up highway scenes, as could be expected. When HD point cloud and VLP-16 data are collected on similar winter conditions, the elevation determination accuracy improves in all scenes as the snowbanks have not altered much.

2.4.3 Lidar based positioning (Sensible 4 approach)

For this section, the discussion is divided into several subsections, i.e. performance of positioning in non-snow and snow driving conditions using the non-snow maps, as well as the performance of positioning during non-snow and snow driving conditions using the snow maps. The speed profiling for the non-snow positioning is shown in Figure 48.

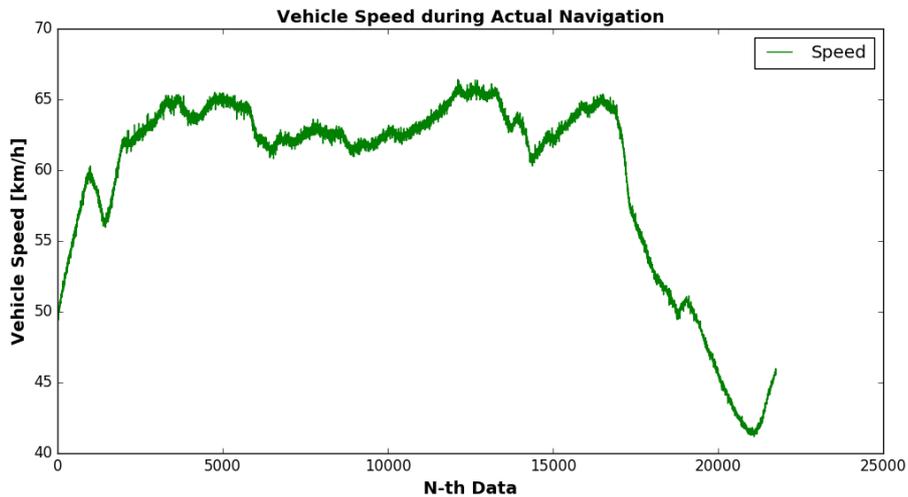


Figure 48. Speed Profiling for the Non-Snow Positioning.

For snowy conditions, the speed profiling positioning is shown in Figure 49, with average speed up to 40 km/h due to slippery road conditions

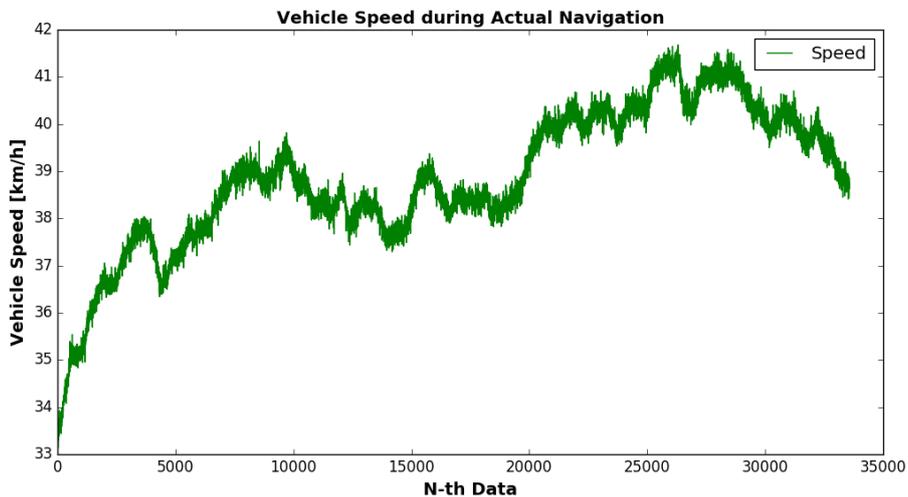


Figure 49. Speed Profiling for the Snow Positioning.

Tracking Error Analysis for Non-Snow Map

An error analysis between the actual position and the desired position for the non-snow map during non-snow and post-snowstorm driving is performed, and the results are presented in Table 24.

Table 24. Mean Square Error (MSE) for X and Y Direction Tracking for Non-Snow and Snow Driving Positioning for Non-Snow Map.

Driving condition	Non-snow	Snow
MSE for X Tracking	0.037473507224	0.0154905598538
MSE for Y Tracking	0.053119394486	0.0205932731632

MSE value is a frequently used method obtained by calculating the Mean Square Error (Difference) between two metrics, and the value closer to 0 indicates the lesser error, while the value closer to 1 indicate a high tracking error. As can be seen, the tested approach provided a maximum of 0.037 for X tracking and 0.053 for Y tracking. As for the average positioning error, the results are presented in Table 25.

Table 25. Positioning Error Average for the Whole Trajectory for Non-Snow and Snow Driving Positioning for the Non-Snow Map.

Driving condition	Non-snow	Snow
Positioning error average (m)	0.264	0.161

Where the average error for the whole trajectory during autonomous non-snow driving is 26 cm, while for snow driving the value of the average positioning error is 16 cm using a tested approach. A piecewise comparison between both of the reference trajectories and the actual vehicle position using our solution in both conditions is shown in Figure 50.

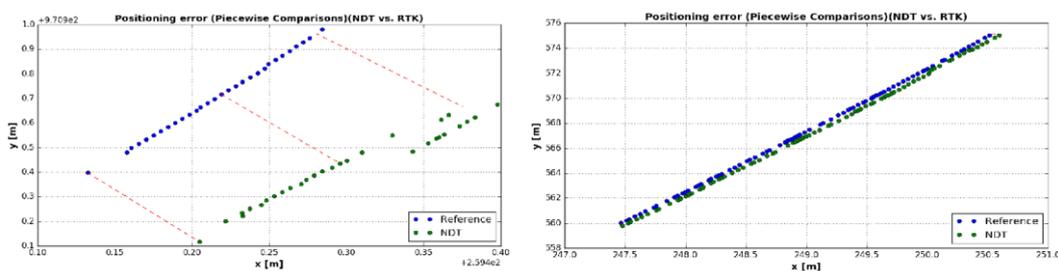


Figure 50. Piecewise Comparison of the Positioning Performance Analysis between Actual Navigation (NDT) and Reference (RTK) for Non-Snow Driving (left) and Snow Driving Positioning (right) Using the Non-Snow Map.

Tracking Error Analysis for the Snow Map

An error analysis between the actual position and the desired position for the snow map during non-snow and post-snowstorm driving is performed, and the results are presented in Table 26.

Table 26. Mean Square Error (MSE) for X and Y Direction tracking for Non-Snow and Snow Driving Positioning for Snow Map.

Driving condition	Non-Snow	Snow
MSE for X Tracking	0.0273621486467	0.0213268250033
MSE for Y Tracking	0.0520886514245	0.0258621142273

As can be seen, the tested approach provides a maximum of 0.027 for X tracking and 0.052 for Y tracking. As for the average positioning error, the results are presented in the table below:

Table 27. Positioning Error Average for the Whole trajectory for Non-Snow and Snow Driving Positioning for Non-Snow Map.

Driving Condition	Non-Snow	Snow
Positioning Error Average (m)	0.236	0.182

Where the average error for the whole trajectory during non-snow driving is 23.6 cm, while for snow driving the value of the average positioning error is 18 cm using the tested approach. A piecewise comparison between both of the reference trajectories to the actual vehicle position using our solution in both conditions is shown in Figure 51.

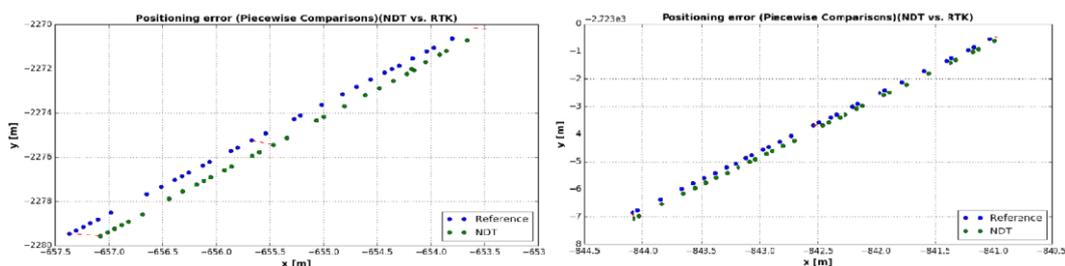


Figure 51. Piecewise Comparison of the Positioning Performance Analysis Between Actual Navigation (NDT) and Reference (RTK) for the Non-Snow Driving (left) and Snow Driving Positioning (right) using the Snow Map.

3 Conclusions

3.1 Posts and poles

3.1.1 Active poles guidance

The active poles guidance was tested very carefully, taking into account the major relevant issues with the novel UWB technology, poles installation and positioning, different speeds and winter conditions. Based on the tests it can be concluded that:

- Measurement accuracy was well within a few centimetres in real winter road conditions across a wide range of distances. All indications are that UWB distance measurement performance is sufficient for navigation along the road.
- When calculated over 100,000 measurements, the distance error is approximately normally distributed with a standard deviation of 27 mm.
- The error deviation is smaller with faster data rates (22 m with 6.8 Mbps vs. 33 mm with 110 kbps).
- The tested set-up achieved a range of close to 100 m and by improving the set-up much longer ranges can be achieved.
- The distance measurement error is independent of distance.
- Weather does not affect UWB range or accuracy based on these tests
- At higher speeds (>55km/h), positioning accuracy deteriorated with the current test set-up.

To improve the test set-up, focus should be placed on improving the installation of the UWB beacons. The installation of an active landmark network needs several aspects to guarantee sufficiently long coverage range, distance and position accuracy, reliability and redundancy in changing weather and traffic situations. The issues that were identified and should be resolved are:

- Installation for good coverage range and accuracy: A vehicle navigating with active UWB landmarks needs line of sight (LoS) visibility to a minimum of three active poles at a time to calculate the position. A line of sight signal path is needed to keep the coverage range long enough and to keep the accuracy of measurement good enough. For this purpose, beacons need to be installed high enough to avoid the rising level of snow, and if possible, higher than smaller cars and people.
- Current UWB technology beacons need 15cm of non-radio reflective space around them to work properly in all LoS directions. This means independent poles or extension arms from other metallic constructions like light or traffic sign poles.

- Installation related to the power: The active use of current UWB technology roughly needs the power of 1W, which means bigger batteries and recharging or continuously wired delivery of power. For the previous reasons, light poles or active traffic signs with existing power supply are potential installation places for beacons.
- Installation related to long-term reliability: Active UWB beacons can be positioned in real coordinates in two ways: either fixing them to a specific coordinate position or by a self-positioning method, where the beacon network calculates the position for each beacon.
- When a self-positioning method is used, it is essential to reserve LoS visibility from each beacon to a minimum of four other beacons inside the coverage range.

Positioning with proper poles and installations seems to be adequate for proper vehicle positioning. However, there are many related problems, let alone the need for constant electricity that may harm the wider utilisation of UWB poles-based solutions.

3.1.2 Passive posts and poles with reflectors

To fully utilise the radar potential for automotive applications under extreme weather conditions, we have conducted a research study that focuses on testing passive roadside radar reflectors. The study contributes to the understanding of the prospects and limitations of current technologies and products in the field of autonomous driving with a focus on radars and reflectors. (Händel C, Saarenpää T & Autioniemi M, 2019)

Three radar systems were tested that were suitable for transport applications. 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 forms and sizes 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, a tubular reflector pole was designed and an experimental set-up on a road was developed. (Händel C, Saarenpää T & Autioniemi M, 2019)

In **the first part**, the test field background without reflector poles was studied. The characterisation of objects along the road, such as roadside furniture, was the prior goal of this measurement. The surroundings of the road are characterised by multiple radar reflections. These reflections are caused by, among other things road signs, bus stops, large trees and house roofs. The road itself is free of radar reflections. Further, different objects along the roadside were detected at different vehicle speeds. The results indicate that higher vehicle speeds lead to lower detected RCS values. In **the second part**, the test field including 97 self-designed tubular reflector poles was monitored with our test vehicle. The test should clear up whether 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 at a driving speed of 80 km/h. This result is particularly important because all the previous tests were performed at 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 back-

scattered 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 are at a larger lateral distance from the radar than the corresponding poles on the right side. The measured RCS mean values (signal strengths) for the poles are $\sigma_{\text{right}} = (65 \pm 4.9) \text{ m}^2$ and $\sigma_{\text{left}} = (49 \pm 3.3) \text{ m}^2$. 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 up to three times larger. The data shows further smaller standard deviations for the detected RCS in the near range area compared to long-distance measurements. **The third part** focuses on the influence of 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. 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, that means at longitudinal distances between 0 and 70 m, is on average more accurate than in the far range area. The measured data is in good accordance with Scherr et al. (2015). (Händel C, Saarenpää T & Autioniemi M, 2019)

Moreover, the results show that the self-designed reflector poles are detectable at all tested speeds in the near and far range areas. At higher speeds, peak values in the RCS were no longer detected. This leads to lower detected RCS mean values. The effect of oncoming cars on the detectability of the reflector poles are studied in **the fourth part**. The results show that oncoming cars can be detected by the radar sensor from Continental up to a longitudinal distance of 250 m. The detected signal strength of the cars is in the range of our radar reflectors. In particular, 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 ($v = 80 \text{ km/h}$). In that case the poles on the right side are of essential importance. Oncoming cars did not block the sightline between the radar and the reflector poles on the right and the left side of the road simultaneously. Finally, the influence of snowdrifts on the detectability and positioning of the self-designed reflector poles is discussed in **the fifth part**. The results indicate that snowdrifts weaken the detected RCS of the reflector poles. The data further shows that the positioning of the reflector poles is less accurate if there are snowdrifts between the reflector poles and the test vehicle (radar). Another result is that, in unfavourable conditions, a large lorry in front of the test vehicle can obstruct the signal between the radar and those reflector poles that 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. (Händel C, Saarenpää T & Autioniemi M, 2019)

Finally, it can be stated that the present study contributes to the understanding of the prospects and limitations of current technologies and products in the field of autonomous driving with a focus on radars and passive reflectors. The present feasibility study should also act as a basis for a future commercial application of the developed reflector poles. The results give a positive prognosis for developing the radar reflectors further and making them smaller for more practical and cost-effective solutions. Smaller reflector diameters ($\approx 11 \text{ cm}$) would open up the possibility to include the reflectors in one single pipe instead of using a more complex geometry, as presented in current study. Smaller reflectors could be compensated by adding more of them inside the pipe.

Instead of having three there could be nine or even more. Our self-designed reflector poles in combination with night reflectors would further support driving in poor environmental conditions, such as darkness or fog. (Händel C, Saarenpää T & Autioniemi M, 2019)

3.2 Cooperative Intelligent Transport Systems (C-ITS)

Testfest 1 examined the transmission of Day 1 messages by using a hybrid solution that combined the ITS-G5 and LTE technologies under arctic conditions in the Aurora pilot site. Testfest 1 provided important experience on technical functioning of the hybrid solution and the communication of Day 1 messages in arctic conditions. In addition, a notable mileage was driven with the VTT's automated vehicle Martti, and a remarkable amount of data related to automated driving was collected in Testfest 1. Dissemination of two Day 1 messages using the hybrid solution based on ITS-G5 and LTE technologies was tested in Testfest 2. The tests produced quantitative results on, for example, the performance and geographical coverage of the ITS-G5 and LTE technologies and information on potential cross-border interoperability of the messages. In Testfest 3, the latency of I2V and V2X Day 1 services was measured and the functionality of four Day 1 messages was tested using the hybrid solution based on ITS-G5 and LTE technologies.

Technical functioning of the services

During the three Testfests of the Arctic Challenge project, four C-ITS Day 1 messages were successfully communicated using solutions based on the ITS-G5 and LTE technologies. Based on the results of Testfest 1, it is justifiable to conclude that the ITS-G5 and LTE solutions used for the transmission of Day 1 messages are functional under arctic conditions. This conclusion applies to situations in which systems and communication networks operate in their normal state. Analysis on the operation of Day 1 services in situations where the mobile network is exceptionally congested fell outside of the scope of the study.

The results of Testfest 2 suggest that, in addition to the specifications and technological implementation of Day 1 services, the reliable and safety-improving operation of the services is based on the correct configuration of the systems providing the services. This involves, for example, specifying the range and duration of Day 1 messages and ensuring that an excessive number of messages is not sent regarding the same event or situation. In addition, the results of Testfest 2 suggest that the implementation based on the ITS-G5 technology was, at least at the time of conducting the tests, more mature for dissemination of Day 1 messages than the solution based on the LTE technology.

Testfest 3 focused particularly on measuring the latency in transmission of I2V and V2X warning messages. The results of Testfest 3 suggest that all or nearly all I2V warnings sent in the test environment were received by the on-board unit within 25 seconds of publishing the warning at the TDAC. This result applies to both ITS-G5 and LTE on-board units, but it is marked by a certain degree of uncertainty as the clocks of the LTE on-board units could not be synchronised with the accurate time provided by the GPS or the NTP. Furthermore, the result is based on a limited number of warnings sent and received during a single day.

Therefore, the need to verify the result through more extensive tests is justifiable.

The latency of V2X warnings was measured in an environment where the stopping vehicle, that generates the warning, uses the ITS-G5 technology for sending information on its status as CAM messages to a C-ITS road side unit. The road side unit (RSU) then forwards the messages to a cloud service (CCSP) which in turn forms a DENM indicating a stationary vehicle. Since the clocks of the ITS-G5, LTE and pre-5G on-board units receiving the messages were synchronised with different time references, a comparison of the exact message reception times could not be conducted.

At least part of the latency of the system tested in Testfest 3 has to do with the selection of parameters used in the implementation of the system as well as the technical implementation of the system. For example, retrieval of warning messages from the TDAC to the CCSP was apparently implemented with standard intervals instead of event-driven operation. It should be possible to further lower the latency by shortening this interval or by implementing event-driven message transfer.

How should the analysed Day 1 services be implemented?

Four Day 1 services were analysed in the study: stationary vehicle warning, animal on the road warning, slippery road warning and roadworks warning. The latency values measured in Testfest 3 should be sufficiently low for at least a basic level implementation of these services. Roadworks and maintenance sites generally remain in the same location for longer periods of time, or if they move, the movement is slow (e.g. paving sites). Weather and road conditions may change relatively suddenly, but many changes, such as accumulation of ice on road surface and the reduction of visibility are at least partially predictable. Animals may move unpredictably in the road environment, and potentially dangerous situations may start and end abruptly. Therefore, lowering the latency below the values measured in Testfest 3 may be worthwhile in connection with warnings concerning animals on the road.

The alternative Day 1 service implementations examined in the study still require further testing, more extensive study of their operation in realistic environments and cost-benefit analyses. The results of the CBAs are affected by the investment costs of service implementation.

The implementation based on the ITS-G5 technology requires the installation of C-ITS road side units along the road network. Based on the results of Arctic Challenge Testfests 2 and 3, a single RSU can reliably transmit messages up to a distance of 400–800 metres. Achieving this range most likely requires that the terrain features and structures in the road environment do not prevent radio propagation with the line of sight. In addition to a physically suitable installation site (e.g. a pole), C-ITS RSUs require power supply and a fixed-line or wireless data connection. In the alternative based on the ITS-G5 technology, the installation and maintenance costs of the required roadside ICT infrastructure may be substantial.

The advantage of the ITS-G5 technology is that its performance is not affected by the load of the mobile network or the status of frequencies used by mobile networks. This applies to situations in which the roadside units have the capability to generate warning messages (DENMs) autonomously or they have a fixed-line data connection which can be used to send warning messages to RSUs for example from a cloud service or a traffic control centre. This property is advantageous in situations where the number of calls or the volume of transferred data may increase abruptly over regular levels (e.g. disaster situations and high-density urban environments).

LTE networks provided by various operators as well as the private network provided by Ukkoverkot (Ukko Networks) were available in the Aurora Borealis Corridor. Telia's LTE network, which was used in the tests, covered the pilot site entirely or almost entirely, and it enabled achieving an extensive Day 1 service coverage in the Aurora Borealis Corridor. Two C-ITS RSUs were accessible in the Aurora Borealis Corridor. The RSUs were installed close to the town centre of Muonio, and they enabled the implementation of Day 1 message transmission in a road section of approximately 1–2 kilometres using the ITS-G5 technology. As the expenses of covering the entire Aurora Borealis Corridor with C-ITS RSUs would have been high, such degree of coverage was considered infeasible when planning the tests. Based on the results of the Testfests, the particular advantage of the LTE technology is that it allows providing a geographically extensive Day 1 message coverage with relatively reasonable investments.

Situations where mobile network congestion or a weak signal would have prevented or remarkably hampered the transmission of Day 1 messages were not observed during Testfests 1, 2 or 3. Therefore, the implementation based on the LTE seems a viable solution for dissemination of Day 1 messages. However, the data generated during Testfests 1, 2 and 3 was collected over the course of a few days in limited areas and mostly using a single network. Therefore, conclusions based on the data may not be applicable to periods of time or geographical locations where the mobile network capacity is subject to heavier-than-normal loads. In any case, the service level provided by LTE networks depends on the investment decisions of network operators.

The results suggest that the utilisation of ITS-G5 RSUs for the implementation of Day 1 services may be justifiable in situations where the transmission of messages with a low level of latency is of particular importance due to the nature of a specific location or service. In addition, the use of ITS-G5 RSUs is advantageous in situations and sites where there is a need to provide a telecommunications channel which is independent of the quality and load of the mobile network.

Which Day 1 services should be implemented in the Aurora Borealis Corridor?

The Aurora Borealis Corridor is a section of a single-carriageway arterial road whose traffic volume is relatively low. Currently, the Aurora Borealis Corridor is not equipped with roadside systems applicable for the detection of stationary vehicles or animals moving on the road. Considering the current traffic volumes on the road, installation of such systems would not be a reasonable investment from the socio-economic point of view. On the other hand, on-board sensor detection would require a sufficient level of penetration among vehicles driven on the road. As a large part of the Aurora Borealis Corridor's traffic consists of through-traffic, reaching a sufficient penetration is likely to take a long time.

The Aurora pilot site is located within a reindeer herding area which may increase the frequency of traffic incidents caused by animals on the road. The collection of data concerning animals (e.g. reindeer) or stationary vehicles on the road should be feasible based on notifications sent by road users. However, this would require establishing a service for the reception of road user notifications.

On the other hand, it should be possible to provide weather- and road condition related warnings that improve the safety of road users with the existing infrastructure using weather forecasts and up-to-date road weather information. The implementation of roadworks warnings is based either on work plans provided to the traffic centre in advance or on on-board units installed in maintenance vehicles communicating with back-office systems and roadside units. The cost of equipping maintenance vehicles with suitable C-ITS on-board units would likely be limited.

The successful exchange of C-ITS messages between different service operators is a prerequisite for the implementation of an efficient information and warning service with cross-border interoperability. There is currently a strong drive for the development of a C-ITS ecosystem in Europe. Cross-border interoperability of C-ITS has been promoted simultaneously with the performance of this study by preparing and implementing the pan-Nordic NordicWay 2 deployment pilot in which Finland participates actively. The architecture of the back-office systems used in this project supports the ongoing development, enabling the utilisation of the received results in the future. Interoperable services enable, for example, improving the flow and safety of logistic operations (e.g. salmon deliveries) in the Aurora pilot site transport corridor by allowing exchange of Day 1 messages between operators.

Of the Day 1 services tested in the Arctic Challenge, the weather and road condition warning and roadworks warning are particularly suitable for implementation in the Aurora Borealis Corridor in the initial stage. Stationary vehicle warnings and animal on the road warnings can also be implemented in the area if the information required for generating the warnings can be collected.

3.3 Remote control and communication infrastructure

It is obvious in the tested use case that with limited resource, the 5G test network will be the emerging technology in the next few years and it will have a huge impact on vehicular communication. The 5G real network will focus on very high data rates with very low latency, praiseworthy user experiences in densely populated areas, vehicular communication, proficient management of several devices and reliability. Even the limited tests done by S4 consortium with the 5G test network support the fact that 5G will be important for the use of autonomous vehicle data transferring and remote-control intervention.

Based on the result, it can be concluded that the concept proposed in this report is useful for the safety purpose of varied types of autonomous vehicles, particularly in remotely operating the vehicle in scattered environments and accident locations, among many others. For improved network latency reliability, the 5G connection should be considered for the use of autonomous vehicle remote operating and monitoring purpose. This in return would lead to

more secure autonomous vehicle navigation. The 4G connection can be used for over the network remote control collision avoidance operation, but for reliability reasons the connection should be duplicated to different network carriers. Regardless of this, the remote control test shows that 5G is desirable for larger data transfer.

3.4 Vehicle positioning

GNSS

In Arctic conditions, RTK-GNSS positioning could be used as one of the sources of positioning and also as a basic truth for future analysis of different positioning methods. However, special attention to no-Fix RTK-GNSS should be directed both at autonomous driving as well as to tests where RTK-GNSS is used as a basic truth.

HD Maps (SolidPotato approach)

Based on the series of validations carried out in the topics of positioning, it can be concluded that the Lidar-based positioning utilised in this work provides the best practice for the positioning strategy of autonomous vehicles in northern non-urban areas with a harsh climate. However, the information gained from the HD Maps is also described below:

- When the geometry of the applied sensor (VLP-16) and the built environment features matches (case rock cut), and when using an HD map taken the same day, an accuracy of 4–5 cm could be obtained, which is the maximum accuracy possible for detecting with our reference data.
- When the geometry of the applied sensor and built environment features do not match properly, and even when using an HD map taken the same day, an error of 0.5 m was observed for road crossings. The major reason is the long SLAM processing time (5 s) and a lack of features in the surroundings when using VLP with parallel scan lines. If there had been more vertical features such as poles or sticks, the localisation accuracy could have been much better.
- The worst results were obtained when there were a large amount of open space and a lack of map matching features during the 5 s SLAM integration time.
- Even trees and forests could act as a feature for improving positioning.
- The environment, whether it provides an adequate number of features to be used in SLAM and HD map matching or not, was of higher importance than the seasonal effect.
- There was enough correlation between the point clouds and HD, even though the HD map was taken in all seasons.
- Typical accuracy for vehicle positioning was 20–30 cm based on our integrated SLAM and HD map matching approach, which was implemented to give an upper boundary error for autonomous vehicle localisation, and it varied between 5 and 50 cm, mainly based on the

availability of the number of features in the surroundings. Consequently, the increase in the number of objects feasible for point cloud matching, such as snow sticks used to guide snow ploughs, are a good way to improve the positional accuracy of autonomous cars in an easy way.

Consequently, it can be concluded that the testing and demonstration done by the Solid Potato proofs using SLAM and HD maps adequately showed that autonomous localisation does not require any additional infrastructure-related systems. The proper localisation was reached with reasonably different weather and winter conditions.

Lidar-based positioning – Sensible 4 approach

According to the testing and analysis, Lidar-based positioning was performing successfully. However, for better navigation, particularly in the case of slippery surfaces, an improved high-level controller for the trajectory tracking performance is desirable. Overall, it can be concluded that the solution used by Sensible 4, a combination of multiple sensors as well as non-linear algorithms with the satellite information yield a reliable positioning performance of an AD vehicle, with the maximum average error of 0.264 m in all conditions using the same one map. This error also includes the possible error of basic truth, RTK-GNSS.

Table 28. Summary of the positioning analysis, Sensible 4 approach, results with multi-condition driving using non-snow and snow maps.

Map	Non-snow	Non-snow	Snow	Snow
Positioning Driving Condition	Non-snow	Snow	Nonsnow	Snow
Average Positioning Error (m)	0.264	0.161	0.236	0.182
Y-Axis Average Error (m)	0.187	0.105	0.166	0.117

To summarise the findings, Table 28 states all of the average positioning errors in all proposed scenarios. From the results discussed in the previous section, it can be seen that the solution used by Sensible 4, a combination of the multiple sensors as well as non-linear algorithms with the satellite information yield a reliable positioning performance of an AV vehicle, even in rural Arctic conditions, with the maximum average error of 0.264 m and lateral error of 0.187 m in all conditions using a single map.

4 Discussion

The study of posts and poles in Arctic conditions contributes to the understanding of the 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 that snowdrifts weaken the detected signal of the reflector poles, and 20 m pole intervals considered advantageous at 80 km/h speeds in traffic with possible other vehicles blocking the signal. The results give a positive prognosis for developing radar reflectors further and making them smaller for more practical and cost-effective solutions. (Kotilainen et al. 2019). UWB positioning is currently useful in closed systems, but more research and cooperation is needed to create standards and regulations to allow international compatibility and the wide adaptation of this technology.

To allow AV to be used in rural areas, Vehicle-to-Infrastructure (V2I) and Vehicle-to-Vehicle (V2V) implementation should be widely utilised. This will enable the AV to develop a better-decisioning strategy, particularly in the context of collision avoidance and hazard mitigation. The proper market solutions will be available when the general concepts, best practices and standardisations have reached the required level. There are also some more general problems to overcome when thinking about deployment related to system solutions and cooperation with operators, business models and users, for example. Large road network coverage requires advanced IT systems and the effective public-private operation and management of major traffic flows.

The research results achieved so far on automated vehicles (AV) indicate that Remote Control is a possible solution for safe driving in northern latitudes. From the findings of Remote Control, as can be seen, 5G connectivity is required to enable a comprehensive remote operator operation for AVs. Thus, collaboration with the whole ecosystem with automotive and telecommunication industries are expected to improve connectivity issues.

For positioning, research should be performed to develop a wider geofencing region for HD maps with large-scale test fleets and longer durations. This in return will allow for the more extensive deployment of AV, particularly in rural areas, where AV can be used in the context of health, military and surveillance purposes, for example. Additionally, the sensor fusion of different localisation methods should be further tested to ensure the AV will benefit from reasonable localisation accuracy in different scenarios. At the same time, a lot of effort is also directed at sensor development, which should go hand-in-hand with software development.

The technology and solutions for automated driving are rapidly developing, both through OEM's actions and also through research coalitions and projects. Today and annually, many new development activities are launched because automation is one of the major challenges in the transport system and its different modes of development. For the time being, no major research and development activities are being launched dealing in particular with the harsh weather conditions that are present at northern latitudes. Some testing has been going on in US, for example, but it seems to be of major importance to continue the development activities to secure and enable automated driving in harsh weather and road conditions. The public and private sectors seem to be moving into an Operation Design Domain (ODD) approach in the regulating and

development of ADs. The Nordic countries should take a leading role in ensuring that the ODD for non-optimal conditions is developed in PPP collaboration.

A lot more work on solving the problems of harsh weather for automated driving is required. Technology development is going on internationally at full speed. The Nordic cooperation and development activities are considered as one of the key hotspots in autonomous driving, despite there being many automotive companies and major roles in winter testing with vehicles. Rural conditions seem to require the development and implementation of a proper Operational Design Domain (ODD) and systems developed accordingly, enabling the necessary vehicle-infrastructure-communication cooperation. Furthermore, good international cooperation with the major players is required, e.g. participation in the EU and other large development projects together in Public-Private-People partnerships.

The Arctic Challenge results should be discussed together with the relevant experts, including road maintenance and other industry members, to further evaluate the results. Future decisions on the physical and digital infrastructure require strategic public and private collaboration. This collaboration is taking place at the moment in the report publication in the European Commission-established CCAM Single Platform. Further research is encouraged on post and pole radar reflectors and the market need for them, as well as cost efficiency. Other vehicle positioning methods such as UWB and lidar, together with other sensors, is also encouraged. Further development and studies of the communication networks and Cooperative ITS provide advantages for automated vehicles and drivers to avoid dangers and obstacles in the changing traffic environment.

Sources

Aurora. 2019. Aurora-älytie ja avoin kokeiluekosysteemi - hankkeen loppuraportti (engl. Aurora intelligent road and open test ecosystem - final report). Available online in www address:

https://julkaisut.vayla.fi/pdf12/vj_2019-22_aurora-alytie_web.pdf

European Commission. 2016. A European strategy on Cooperative Intelligent Transport Systems, a milestone towards cooperative, connected and automated mobility. COM (2016) 766 final. Available on web page:

https://ec.europa.eu/energy/sites/ener/files/documents/1_en_act_part1_v5.pdf

Finnish Transport Agency, Lumiaho & Malin. 2016. Road Transport Automation Road Map and Action Plan 2016–2020. Research reports of the Finnish Transport Agency, 19eng/2016. Available on web page: https://julkaisut.vayla.fi/pdf8/lts_2016-19eng_road_transport_web.pdf

Finnish Transport Infrastructure Agency (2014). Tieturva 1 (engl. Roadwork Safety Card, level 1). Available online in web address:

https://julkaisut.liikennevirasto.fi/pdf8/lop_2014-03_tieturva_1_web.pdf

Finnish Transport Infrastructure Agency (2012). Tieturva 2 (engl. Roadwork Safety Card, level 2). Available online in web address:

https://julkaisut.liikennevirasto.fi/pdf3/lop_2012-03_tieturva_2_web.pdf

Händel C., Konttaniemi H., Autioniemi M., (2018). State-of-the-Art Review on Automotive Radars and Passive Radar Reflectors: Arctic Challenge research project. In: Sarja B. Tutkimusraportit ja kokoomateokset, Lapin ammattikorkeakoulu. URN:ISBN:978-952-316-223-5.

<https://www.theseus.fi/handle/10024/144521>

Kotilainen, I., Santamala, H., Öörni, R., Nykänen, L., Schirokoff, A. & Fienadt, N. 2019. Connected and automated driving in snowy and icy conditions – results of four field testing activities carried out in Finland. Unpublished draft version, submitted to Transport Research Arena 2020 (TRA 2020).

Lumiaho, A. & Malin, F. 2016. Tieliikenteen automatisoinnin etenemissuunnitelma ja toimenpideohjelma 2016–2020. Research reports of the Finnish Transport Agency 19/2016. Finnish Transport Agency, Helsinki. https://julkaisut.vayla.fi/pdf8/lts_2016-19_tieliikenteen_automatisoinnin_web.pdf [accessed 16 August 2019].

Nykänen, L., Kostainen, J., Lankinen, M., Pöyhönen, A. & Ylisiurunen. 2019. Lessons learned from Arctic Challenge hybrid C-ITS field tests. Proceedings of 13th ITS European Congress, Brainport, the Netherlands, 3–6 June 2019.

Nykänen, L., Kutila, M., Lankinen, M., Pöyhönen, A. & Ylisiurunen. 2018. C-ITS testing and piloting in Nordic conditions: case Finland. Proceedings of 25th ITS World Congress, Copenhagen, Denmark, 17–21 September 2018.

Traffic Management Finland Group (TMFG). (Referred in 2019, November). Aurora Intelligent Road. Web: <https://tmfg.fi/fi/road/aurora-intelligent-road-section-e8>

Öörni, R. & Nykänen, L. 2019. Arctic Challenge, Preliminary Results. Presentation at NordicWay2 Workshop on Findings from Arctic Challenge, 22nd May 2019, Gothenburg, Sweden.



ISSN 2490-0982
ISBN 978-952-317-739-0
www.vayla.fi