EMC VERification of Autonomous vehicles in reverberation chamber (EMCVERA)

Public report

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Content

Summary

The project aimed to investigate some of the open research questions in the standardization of reverberation chambers and build national competence and capacity in the future EMC verification of Autonomous Driving (AD) vehicles.

Modern vehicles are highly complex with sensors, actuators, control units, high-end user interfaces, communication interfaces, and support systems. The sensors precept internal states, such as speed, as well as information from the surrounding environment (e.g., radar). Electronic Control Units (ECUs) process data from the sensors, make decisions, and sends information to actuators, enabling drive functionality and other functions. Besides functionality to transport the vehicle in a safe and energy-efficient way, a modern vehicle also contains several other systems for, e.g., user experience, product update, or maintenance. AD vehicles are the next, already ongoing step in vehicle automation which will provide means to reduce environmental impact, increase traffic efficiency, safety, and user experience, but boosts the requirements on validations in labs as well as in the field.

The Vinnova/FFI road map ”Strategisk färdplan för Elektronik, mjukvara och kommunikation” can be seen as a concise summary of needs within research and innovation areas for the Swedish automotive industry to enable development of safe and environmental friendly vehicles to stay competitive in an international comparison.
The complex electrical architecture we see in modern vehicles with high-speed communication between sensors, computational/decision making electronic units and actuators constitutes a challenge when it comes to verification and validation to maintain and improve vehicle safety in the transport system.

The purpose and goal of this project are to increase reliability and cost efficiency during EMC validation of AD vehicles. This will be achieved by utilizing the reverberation chamber during EMC validation of vehicles as a complement to the absorber lined shielded enclosure method, which is the most-widely used method today. The expected results were:

- The project should deliver a state-of-the-art EMC test method adopted for the development of reliable AD vehicles.
- A test method that increases confidence in EMC testing at the higher frequencies that will be used in many technologies in automated vehicles, e.g., communication and sensor technologies, without the need of drastically increased expensive testing time.
- A test method with an improved detection rate of any EMS issues.
- A test method with an improved accuracy regarding EMC test level.
- Swedish national competence and capability in EMC testing for the future.

The project consortium believes that we, by the end of the project, met all of the expected results above.

Sammanfattning på svenska

Projektet syftade till att undersöka några av de öppna forskningsfrågorna inom standardisering av modväxlad kammare (MVK) och bygga nationell kompetens och kapacitet i framtida EMC-verifiering av fordon för autonom körning (AD).

Tekniken i dagen premiumfordon är mycket komplex med avancerade sensorer, ställdon, styrenheter, avancerade användargränssnitt, kommunikationsgränssnitt och stödsystem. Sensorerna mäter fordonsinterna tillstånd, som t ex hastighet, samt information från den omgivande miljön (t.ex. radar). Elektroniska styrenheter (ECU) bearbetar data från sensorerna, fattar beslut och skickar information till ställdon, vilket möjliggör funktioner för framdrivning och andra funktioner. Förutom funktionalitet för att framföra fordonet på ett säkert och energieffektivt sätt innehåller ett modernt fordon också flera andra system för t.ex. användarupplevelse, produktuppdatering och underhåll. AD-fordon är nästa, redan pågående steg inom fordonsautomation som kommer att möjliggöra minskad miljöpåverkan, öka trafikeffektiviteten, säkerheten och användarupplevelsen, men ökar samtidigt kraven på valideringar i laboratorier såväl som i fält.

Vinnova/FFI:s färdplan för Elektronik, mjukvara och kommunikation kan ses som en kortfattad sammanfattning av behov inom forsknings- och innovationsområden för svensk fordonsindustri för att möjliggöra utveckling av säkra och miljövänliga fordon för att förbli konkurrenskraftiga i en internationell jämförelse. Den komplexa elektriska arkitektur vi ser i moderna fordon med höghastighetskommunikation mellan sensorer, elektroniska enheter för beräkningar/beslut och ställdon utgör en utmaning när det gäller verifiering och validering för att upprätthålla och förbättra fordonssäkerheten i transportsystemet.

Syftet och målet med detta projekt är att öka tillförlitligheten och kostnadseffektiviteten vid EMC-validering av AD-fordon. Detta kommer att uppnås genom att använda MVK vid EMC-validering av fordon som ett komplement till de halvdämpade skärmrum, som är den mest använda metoden idag. De förväntade resultaten var:

- Projektet ska leverera en ”state-of-the art” EMC-testmetod anpassad för utveckling av tillförlitliga AD-fordon.
- En testmetod som ökar konfidensen vid EMC-provning vid de högre frekvenser som kommer att användas i många tekniker i automatiserade fordon, t.ex. kommunikations- och sensorteknik, utan behov av drastiskt ökad dyr provtid.
- En testmetod med en förbättrad detekteringsgrad av eventuella EMS-problem.
- En testmetod med förbättrad noggrannhet avseende EMC-provnivå.
- Svensk nationell kompetens och förmåga inom EMC-provning för framtiden.

Projektkonsortiet anser att vi, vid projektets slut, uppfyllde alla förväntade resultat ovan.

Projektet var indelat i fyra arbetspaket, WP1-WP4:

WP1 var projektledning och styrning av projektet.

WP2 EMC provmetodologi, var indelat i tre underpaket, WP2A-WP2C.

WP2A Grundläggande EMC provmetodologi i modväxlad kammare. Här undersöktes huvudsakligen de öppna forskningsfrågor som finns inom metoden. Olika metoder att minska metodens nedre användbara frekvens (Lowest Usable Frequency, LUF) provades experimentellt och med stöd av simuleringar. Slutsatserna som drogs av detta var att det är svårt att sänka metodens nedre användbara frekvens i en väl omrörd kammare mer än några få procent i förhållande till det som ges av kammarens dimensioner, längd, bredd och höjd. I detta arbetspaket togs även ett förslag till en alternativ metod att definiera testnivå som sedermera antagits av ISO och idag utgör Bilaga I, i ISO 11451-5 som givits ut under 2023.

WP2B Undersökning av testzon. I detta arbetspaket undersöktes fälthomogenitet i såväl provningskammaren som i kaviteter i det provade fordonet i kammaren. Analys och teori kring kaviteters elektromagnetiska egenskaper samt hur de exciteras i modväxlande kammare respektive halvdämpat skärmrum.

WP2C Ny metod för ”On-boards unit test”. I detta arbetspaket undersöktes om enskilda utrymmen i bilen, kaviteter, t ex motorrum, bagagerum. passagerarutrymme kan användas som en lokal modväxlad kammare. Syftet skulle vara att ersätta den tidskrävande OBT testmetoden beskriven i ISO 11451-3. Försöken visar lovande resultat vad gäller testeffektivitet och repeterbarhet men mer arbete behövs och resultatet är ej publicerat än.

WP3 Genomförande av EMC prov. I detta arbetspaket jämfördes provningens resultat då fordon (personbil och lastbil) utsattes för påstrålade elektromagnetiska fält i modväxlad kammare och traditionellt halvdämpat skärmrum. Resultatet visade att fler möjliga testutfall hittades i modväxlad kammare. Dessutom visade det att inga av de potentiella testutfall som upptäcktes i traditionell provning i halvdämpat skärmrum missades vi provning i modväxlad kammare.

WP4 Resultatspridning. I detta arbetspaket hanterades resultatspridningen genom att publicera vid vetenskapliga konferenser och tidskrifter. Dessutom har en demonstration av metoden och presentation av resultaten hållits för inbjudna deltagare från svenska industriföretag och akademi.

Background

The complex electrical architecture we see in modern vehicles with high-speed communication between sensors, computational/decision making electronic units and actuators constitutes a challenge when it comes to verification and validation to maintain and improve vehicle safety in the transport system. When it comes to electromagnetic compatibility (EMC) as an example, one of the many priorities is to maintain a high confidence in the verification and validation of the complete vehicle in its surrounding cooperative environment.

The development in EMC validation methodologies must comply with needs to handle the real time behaviour in sensing, decision-making and actions needed for these vehicles. High data rate and high frequency technology goes hand in hand. One property of a high frequency antenna for example, is that the radiation pattern varies significantly with angle around it.

This behaviour of a typical antenna is emanating from the laws of nature and in a similar way the susceptibility of a vehicle to incoming radiated electromagnetic field is significantly varying with the angle of arrival of the field toward the vehicle, at higher frequencies.

The higher the frequency, the more angles of radiation toward the vehicle are needed to be considered regardless if it is communication or electromagnetic immunity of the vehicle that is in focus. Work is on-going to strengthen the possibility to use simulations to early predict EMC and physical test methods needs to be able to test this high angular variation in a reliable and cost-effective way.

Today, testing in Absorber Lined Shielded Enclosures (ALSE) is the dominant method for testing EMC on a complete vehicle level, but due to the increased complexity in vehicle architectures, there is an ongoing debate within the automotive EMC research community whether testing in Reverberation Chambers (RC) can improve the confidence in, specifically, Radio Frequency (RF) immunity testing at higher frequencies.

To expose the complete vehicle to a defined field strength level in the traditional ALSE testing, the vehicle needs to be rotated or the antenna needs to be moved around the vehicle to cover major parts of the vehicle. Compared to the ALSE method, which is a deterministic method, the RC method is a stochastic method where the field over time will vary and arrive at the vehicle from all directions, polarizations, and eventually converges to a traceable and homogenous electrical field.

To achieve this in a traditional ALSE method, different polarizations, and incident angles of the field towards the vehicle must be tested sequentially. This makes the testing very time-consuming if a significant number of angles and polarizations need to be tested. The participating Original Equipment Manufacturers (OEMs) all aim at being leading companies in the development of automated vehicles. Methods and tools to support the development constantly need to be developed and evaluated to match the needs defined by new vehicle functions, technologies and market expectations.

When this project started, the International Organization for Standardization (ISO) had released a working draft for an updated standard, WD/ISO 11451-5, based on the joint European efforts to develop the method for complete vehicle testing. To develop the Swedish national competence in this area, prepare for the future possibility to test in Swedish EMC laboratories, and take an important step as pioneers in the digitalization of the automotive industry this project was initiated. The ISO 11451-5 standard have now been released during 2023 with input from this project.

Purpose, research questions and method

The purpose of this project has been to contribute to the effort of ISO to develop and release an international standard for complete vehicle testing, ISO 11451-5, and investigate some important questions from the project partners to be able to adopt the new standardized method in their product development. Another important purpose has been to build national Swedish competence and capability to perform testing with this new method for vehicles, both on the OEM side and on the institute side.

A number of questions from the partners have been important for the project:

- How can a repeatable test level of the electric field strength inside the RC be defined?
- What are the required exposure times of the electrical field to the Vehicle Under Test (VUT)?
- Can this method be used to test and define average shielding between different zones in the vehicle to be used in setting differentiated EMC requirements on components in the different zones?
- Is it possible to use zones in the vehicle as temporary RCs to perform the standard ISO 11451-3, On-board Transmitter (OBT) test more efficiently than today?
- Classical methods in a semi-anechoic chamber can fix the environment for a specified period and maintain constant radiation on to the test object. With an RC tent, aka Vibrating Intrinsic Reverberation Chamber (VIRC) (see Figure 1) this is not possible. Test the hypothesis that this is not a major issue.

Figure 1. Vehicles during RF-immunity test in RC-tent (VIRC).

The activities in the project have been distributed in four work packages (WPs) as can be seen in the schematic Figure 2. WP 1 and 3 have been led by Volvo Cars and WP 2 and 4 by RISE.

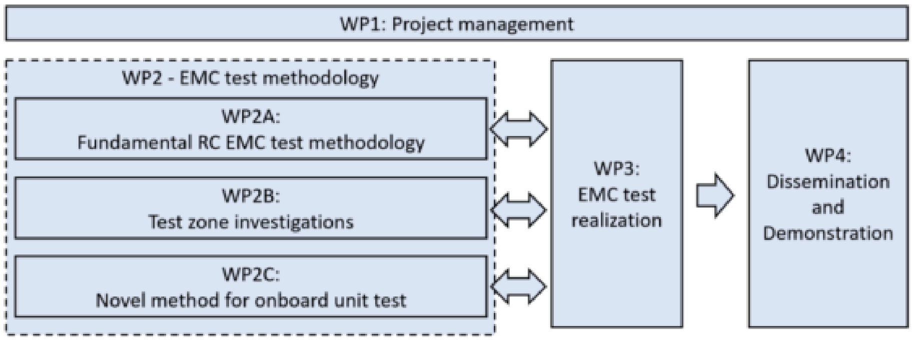

Figure 2. EMCVERA Work Package set up.

The project organization has been kept as efficient as possible, but still following the current best practice for this type of research project. Project management structure has been composed of:

- Steering committee
- Reference group
- Project manager
- Work package leaders

The steering committee consisted of one representative from each project partner.

Each WP leader has been responsible for planning and implementation of the respective WPs and ensures that the associated deliverables did undergo internal review. WP leaders are responsible for ensuring that WPs follow schedules and quality goals and shall report any deviation during the project to the project manager.

Project meeting have followed a quite standardized tradition that worked for the partners with:

- Follow-up meetings every second week. Normally on-line.
- Quarterly meetings with formal progress reporting.
- A number of workshops and test campaigns where all project participants have been invited to enhance the cross-coupling of competence between the partners.

The reference group consisted of representatives from OEMs and other relevant companies not participating in this project, but still interested in its results and potential users of the method: Scania, Toyota Industries, VCE.

Objective

The project objective was to deliver:

- A state-of-the-art EMC test method adopted for the development of reliable AD vehicles.
- A test method that increases confidence in EMC testing at the higher frequencies that will be used in many technologies in automated vehicles, e.g., communication and sensor technologies, without the need of drastically increased expensive testing time.
- A test method with an improved detection rate of any Electromagnetic Susceptibility (EMS) issues.
- A test method with an improved accuracy regarding EMC test level.
- Swedish national competence and capability in EMC testing for the future.

The project also:

- Established a reference group with participants from the Swedish automotive industry for cross-industrial cooperation.

Through ISO, maintained international interconnections and competitive research capabilities for the Swedish automotive industry in the EMC area and set standards for the comprehensive protection of the vehicles.

Results and deliverables

The results from the different WPs are given below. For better understanding of the purpose of the results, the WP descriptions from the application begins each section.

1.1 WP2A – Fundamental RC EMC test methodology

WP2A	Fundamental RC EMC test methodology
Description:	1. Use methods of electronic mode stirring, antenna mast, etc., to reduce Lowest Useable Frequency (LUF) by 20%. 2. Develop and describe a new test level method. 3. Analyze exposure and dwell times in RC. Make comparisons with ALSE tests. 4. Investigate response times of different electronic architectures (HW and SW).
Deliverables:	D2A.1. Report on techniques for extending the lower frequency limit. D2A.2. Report on method for defining and generating a repeatable test level. D2A.3. Report on exposure-time analysis of RC tent (VIRC) methods. D2A.4. Report on response-time analysis of electronic architectures.

For **D2A.1.**, it was investigated if the LUF can be improved. There are several ways to define the LUF of the chamber, e.g., relating it to the chamber dimensions by calculating 100th resonant mode using Weyl's formula (MIL-STD) [1], or by defining the LUF as 3 to 6 times the first chamber resonance [2]. Another way would be performing Goodness of Fit (GoF) tests to determine the stochastic properties of the field distribution in the chamber. The dimensions of the VIRC used in the project were used to calculate the theoretical LUF, in accordance with the methods mentioned above, to be in the range of 62.85 MHz – 125,70 MHz.

The uncertainty in test level, with regard to the electric field, was evaluated by collecting samples, using an electric field probe. The increased uncertainty, as the frequency was lowered towards and further below the LUF, was investigated (see Figure 3). The Cumulative Density Function (CDF) of the data was examined and it shows how the distribution of the samples with increasing accuracy fit the expected Rayleigh distribution as the frequency increases. Below the LUF this is not at all the case. Furthermore, a large discrepancy in level, between the different field components, can sometimes be seen below the LUF, indicating an inhomogeneous field, see Figure 4.

[1] MIL-STD-461E, Department of Defence Interface Standard: Requirements for the Control of Electromagnetic Interference Characteristics of Subsystems and Equipment, August 1999.
[2] IEC 61000-4-21:2011 Electromagnetic compatibility (EMC) - Part 4-21: Testing and measurement techniques - Reverberation chamber test methods.

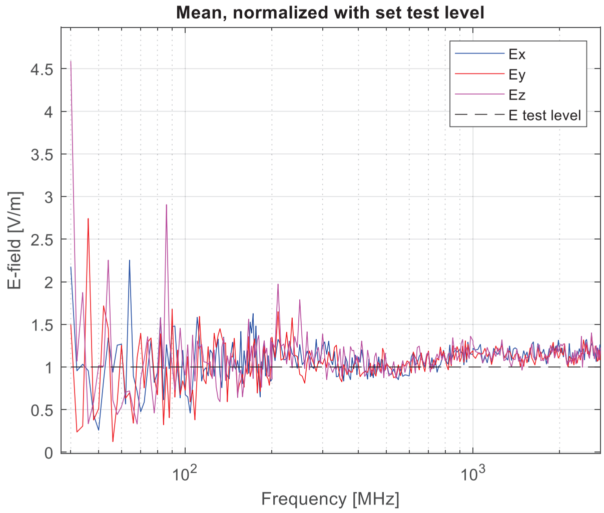

Figure 3. Mean of sampled fields, normalized with set test level (e.g., 100 V/m).

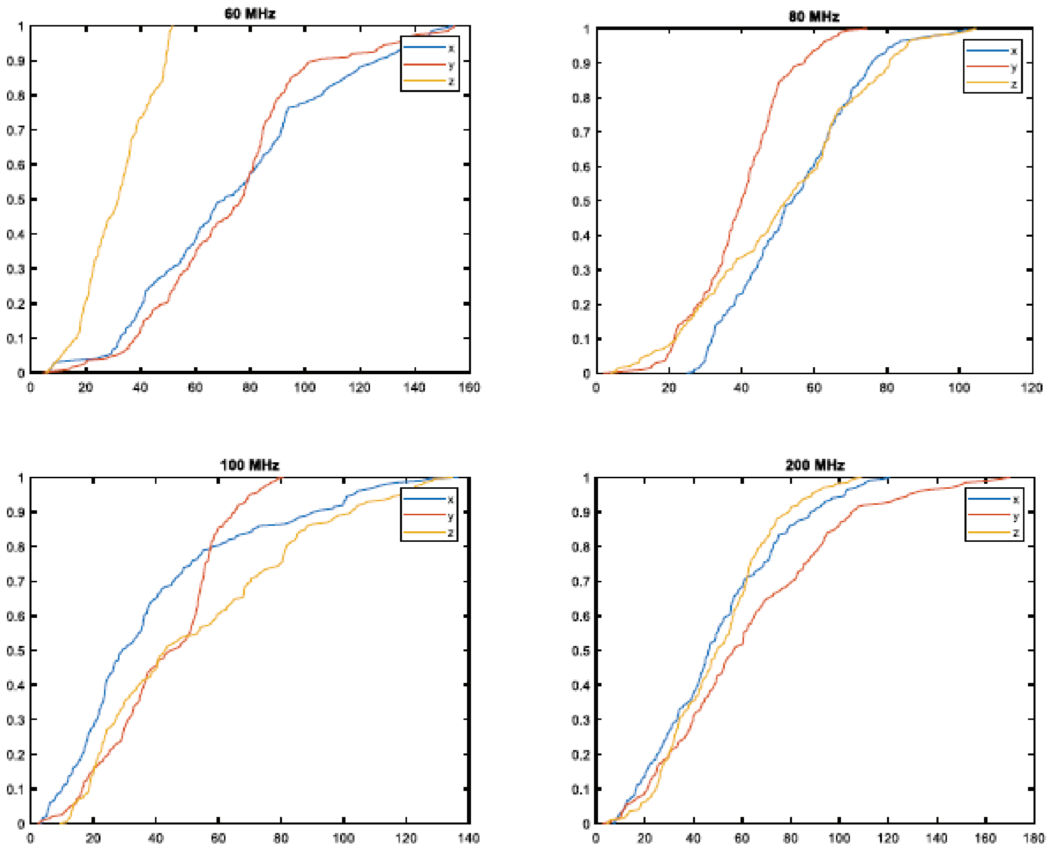

Figure 4. CDFs of electrical field (x-, y-, and z-components) at different frequencies. At 60 MHz there is no Rayleigh distribution, and at 200 MHz data is Rayleigh distributed.

Within this project, it was experimentally evaluated if it was possible to improve the LUF by using two transmitting antennas instead of only one, a type of electronic mode stirring. The results from the investigation did not show any discernible difference in the case of an unloaded RC. However, the use of two transmitters has been shown useful for improving field uniformity for heavily loaded RCs, like the RC tent loaded with a truck.

Simulations were used to investigate and verify that loading the RC with dielectric (non-absorbing) material could be a means to improve LUF, by effectively increasing the electrical dimensions of the RC. The electrical length relates to the physical length by a factor $(\mu\epsilon)^{-1/2}$. This work was published in IEEE conference EMC Europe [1].

For **D2A.2.** we have, in this project, developed an alternative method for defining and generating a repeatable test level, as compared to what has been described in [2]. Instead of searching for the maximum electric field in a statistical distribution, as the Rayleigh distribution (where there theoretically exists no maximum), we propose to define the test level to a quantile with a known offset to the average received power, or to the average electrical field. Especially if a Vector Network Analyzer (VNA) is used to measure the chamber transfer function, the calibration can be performed directly, and efficiently, with the DUT inside the RC.

It was theoretically derived that, for the electrical field, the relation between sample value *x* at a certain probability level *p* to the average value can be found through the formula:

$$\Delta_E = \sqrt{\frac{4}{\pi} ln\left(\frac{1}{1-p}\right)}$$

, which can be used as follows: if the average electrical field is $\langle E_x \rangle$ ($\langle \cdot \rangle$ denotes average), and if the 90% quantile is the immunity target, the test level can be expressed as:

$$E_x^{90\%} = \Delta_{E90\%} \langle E_x \rangle = \sqrt{\frac{4}{\pi} ln\left(\frac{1}{1-0.9}\right)} \langle E_x \rangle \approx 1.71 \cdot \langle E_x \rangle$$

A corresponding expression the received power can be found in [3] which was published at IEEE EMC Europe [3]. See also Figure 5 which plots out electrical field correction as function of probability level to the average electrical field, and the sampled power counterpart. The expressions for electric field as well as power were also verified experimentally. The project proposes predicting and using the 90% quantile to determine the test level. As can be seen in Figure 6 this suggested measure converges with an increased number of samples while the previously suggested, mean of the maximum of the component values, does not.

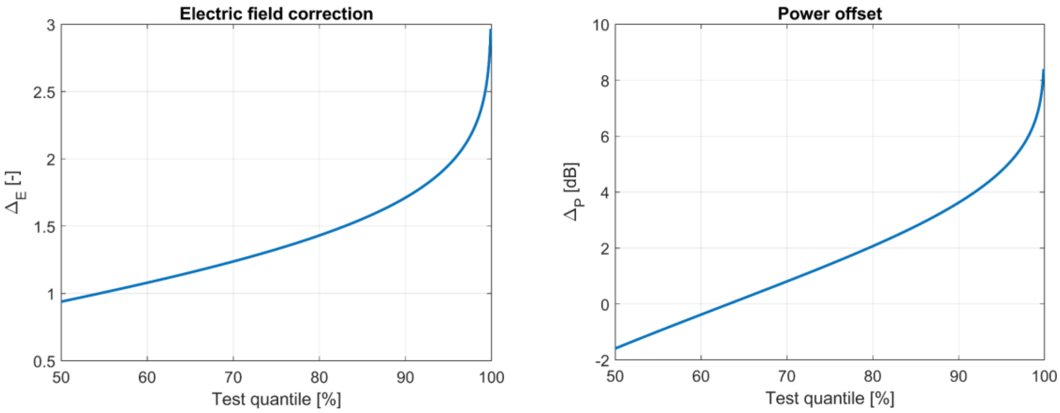

Figure 5. Left: electrical field correction, right power offset, to go from mean value to test quantile.

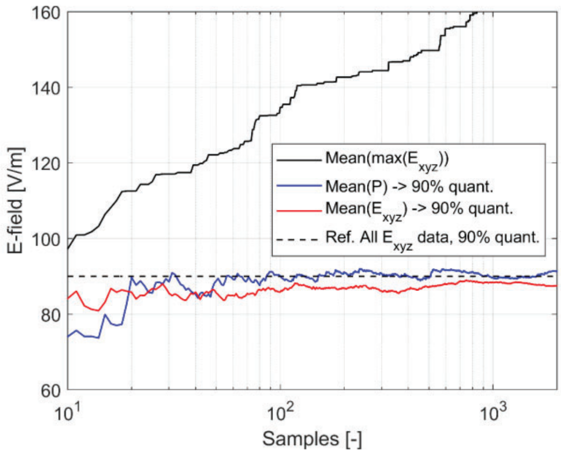

Figure 6. The mean of electrical field maximum values (x, y, and z components) (black) compared with the predicted 90% test level based on the average power (blue), and on the average electrical field (red). The reference (black dashed) is the 90% highest electrical field of the entire dataset (including x, y, z components).

The project has compiled and proposed this power average-based method to the update of ISO 11451-5. After voting it has been accepted as an informative Annex (Annex I). The work of updating ISO 11451-5 is carried out in ISO/TC 22/SC 32/WG 3 "Electromagnetic compatibility". Moreover, the power average-based method as well as the electrical field average method are included proposals in other ongoing updates of EMC standards. The method has also been published in the IEEE conference EMC Europe [3].

D2A.3. focused on exposure time and test time needed for immunity testing in RC. During immunity test in the VIRC it is important to have a correct estimate of the number of independent samples that have been generated onto the vehicle. This is especially important for the test uncertainty as the number of independent samples is the major contributor to the uncertainty budget and is related to the uncertainty budget as the inverse of its square root ($1/\sqrt{N}$). For a specific mode-stirrer setup and sequence in the VIRC, the time between two independent samples (T_u) can be determined by sampling power at the frequency of interest with, e.g., a VNA set to zero-span and then take the autocorrelation of the sampled data and finding the time when the data becomes uncorrelated (i.e., less than 1/e). Finally, the immunity test time, $\mathrm{T_{tes,indep}}$ can be calculated as T_u*<needed test samples>:

$$\mathrm{T_{test,indep}} = \mathrm{T_u} \cdot \mathrm{N_{test}}$$

This relates shortest possible test time to the time between independent samples and can be evaluated for each frequency of interest (example seen in Figure 7).

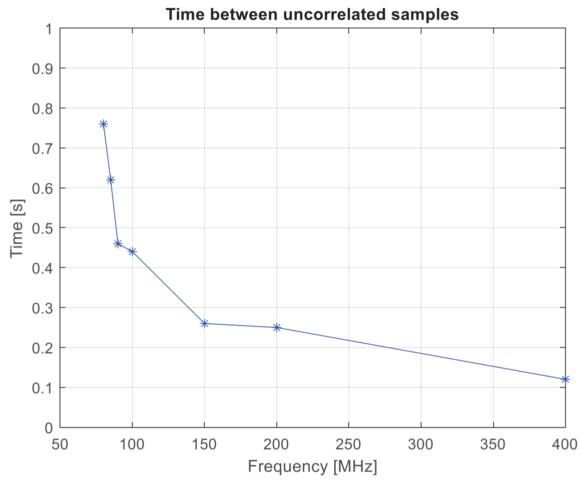

Figure 7. Time between samples in RC tent based on autocorrelation and 1/e limit as function of frequency.

Based on the zero-span measurements one can measure the consecutive time the power (or electric field) is above some test level, e.g., 90%. We define this the *coherent dwell time*.

In turn the *aggregated dwell time* (t_{dwell}) is defined in the project as the total time the power level is above the test quantile, e.g., 90%. In the figures below some 30 s zero-span sweeps are plotted together with the quantile limit. The expected time above the 90% limit is 3 s. This prediction becomes more accurate with increasing frequency.
The data below is sampled in the RC tent loaded by a Volvo V60.

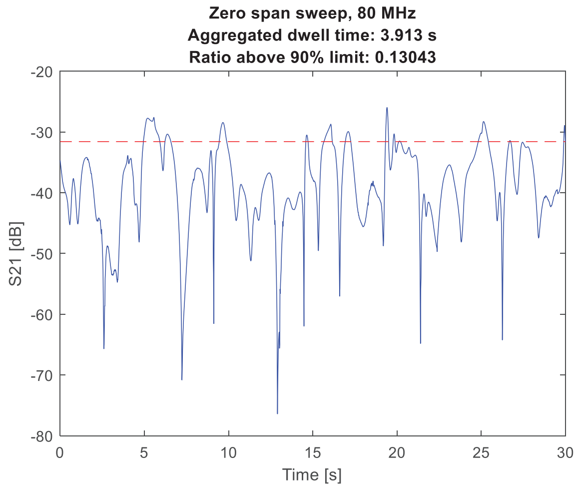

Figure 8. Zero-span sweep with calculated aggregated dwell time at 80 MHz.

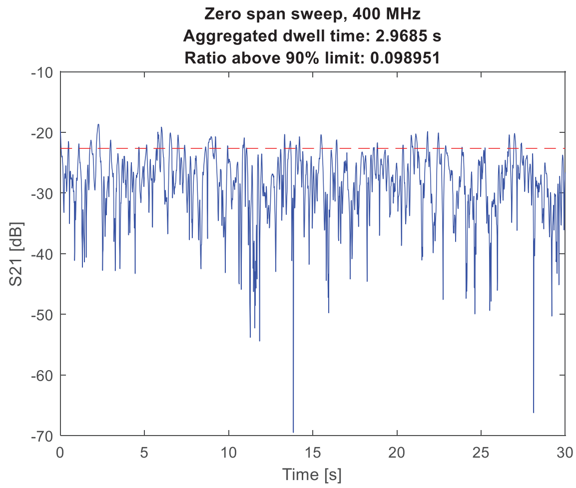

Figure 9. Zero-span sweep with calculated aggregated dwell time at 400 MHz.

The *test time* must ensure both a large enough number of independent samples as well as enough aggregated dwell time and the minimum test time T_{test} for each frequency is thus:

$$T_{test} = max\left\{T_u \cdot N_{test}, \frac{t_{dwell}}{1-p}\right\}$$

When performing an electromagnetic field immunity test of a vehicle the field is applied to the vehicle for a defined time called the exposure or test dwell time. The ISO standardized test dwell time is defined as minimum 1s [ref. ISO 11451-1 2005]. We refer to the dwell time defined by ISO as the "*ISO dwell time*".

For **D2A.4**. it was of interest to investigate if this minimum test dwell time would need to be revised due to the changed test conditions, field statistics in the RC compared to ALSE. If using mode-stirring, i.e., shifting the modes in discrete steps by, e.g., moving the stirrers stepwise, the *ISO dwell time* definition can be used. In the case of mode-tuning, where the modes are shifted continuously, as is the case in the VIRC, no exact dwell time can be defined, but measures to compare the dwell time in the case of a mode-tuned RC to that of an ALSE has been discussed above. In this project we have chosen to set the *test time* such that the *aggregated dwell time* become equal to the *ISO dwell time*. When it comes to the VUT, the time it takes for an electronic module or system to react to an applied electromagnetic field depends on a number of factors. First, the amplitude of the field needs to be above a threshold level corresponding to something called the susceptibility level of the system. Second, the time it takes for the system to respond depends on how quick the system is designed to work in its normal intended function.

A modern vehicle contains a significant number of electronic modules and systems working at time scales from 10^{-10} s (processor processes or multi gigabit communication like GMSL3) to 10^{3} -10^{4} s (make diagnostic error code visible for customer by warning lamp, can be that the error must be present during several drive cycles before warning is visible for customer).

When testing a vehicles immunity to an applied RF electromagnetic field it is impractical and too expensive to expose the vehicle for those longer times at each tested frequency. More realistic is to look into the system and monitor data communication and sensor signals on the vehicle networks and identify error frames or erroneous messages.
The minimum *coherent dwell time* defined by the VUT will in practice be set by the slowest responding systems in the vehicle, the sensor signals with the lowest update frequency and the data communication with the lowest data rate.

In modern vehicles LIN[3] and SENT[4] are examples of communication technologies with the lowest data rate, 20-40 kbit/s, Tire pressure monitoring sensors and ambient temperature sensors in the vehicle are example of sensors with the lowest update rate, typically in the 1-10 Hz region. A minimum *coherent test time* is not only depending on the VUT response time but also on the response time of the monitoring system used to monitor the systems during the test.

Data communication and sensor signal monitoring is realized using electronic test equipment which immediately, within fractions of seconds, can detect an error or a deviation from the expected. However, vehicle immunity testing is also monitored manually via cameras to identify for example warning lamps and other high-level responses that can be visible for a vehicle driver. A too short *test time* would make it very difficult to manually detect an error and connect that to a specific field exposure frequency.

[3] ISO 17987
[4] SAE J2716

Taking both these factors into consideration (response time of VUT and response time of monitoring system) the standardized minimum 1s *ISO dwell time* as *aggregated dwell time* is a reasonable choice when testing modern vehicles.

1.2 WP2B – Test zone investigations

WP2B	**Test zone investigations**
Description:	Firstly, characterize field uniformity in RC and compare with results derived in ALSE. Besides characterization, means will be taken to improve the field uniformity in RC. Secondly, examine transfer functions into and between different closed compartments such as truck cabin, engine compartment, etc. This WP will perform comparisons with the existing standardized ALSE test methods. We will also investigate techniques to generate uniform fields in different test zones. It will also be investigated if EMC requirements on component level can be relaxed due to characterized inter-relations of test zones, which in the long run could save costs for the Swedish OEMs.
Deliverables:	D2B.1. Report on field uniformity and test zones.

This WP covers two important aspects when it comes to vehicular EMC tests in the RC: field uniformity and test zones.

Field uniformity:
Given the presumption of independent samples in the RC, field uniformity is the most important property for measurement accuracy together with the number of samples. Field uniformity is affected by the properties of the RC, stirrer techniques, and test object properties (like size material, etc.). In **D2B.1**, we mainly look at how different test objects affect the field uniformity.

Field uniformity has been sampled by means of two methods in the project: wideband power sampling with VNA, and CW electrical field sampling with electrical field probe. The advantage of power sampling with VNA is the wideband nature of VNA measurements, and on the contrary, its drawback is the size of antennas at lower frequencies. E.g., at 100 MHz an efficient and wideband antenna is typically in the order of 1.5 m. The advantage of electrical field probe sampling is the small size of the probe. This is extra valuable when investigating vehicular cavities. The drawback is longer measurement times due to that each frequency must be tested separately.

The chamber transfer function (G_{RC}) is defined as the average loss from Tx to Rx antenna inside the RC while stirring modes. G_{RC} is measured with the VUT inside the RC as the VUT affects the RF absorption and the statistics inside the chamber according to:

$$G_{RC,dB} = 10 \cdot log_{10}\langle |s_{21}|^2 \rangle$$

where s_{21} is sampled with VNA. The field uniformity is then evaluated by examining G_{RC} for several different positions / combinations of Tx-Rx antennas. In the ideal case G_{RC} would be the same for all positions.

When instead sampling the electric field with an electrical field probe. A reference position is chosen, and the sampled field is then normalized by the average total field at that reference position.

The field uniformity was evaluated for an empty chamber as well as a chamber loaded with either a car or a truck.

The standard deviation, of the average field, over the different antenna position combinations increased at frequencies close to LUF and below. Blocking LOS between antenna pairs was observed to be important for better field uniformity. In the case of immunity testing, this would correspond to blocking the LOS between Tx antenna and VUT.

For a heavily loaded chamber a large-scale fading effect, shadowing, can appear "behind" the truck relative to the Tx antenna. It was shown that using two Tx antennas in heavily loaded situations (i.e., electronic mode stirring) is a useful method to reduce the shadowing effect and improve field uniformity (Figure 10).

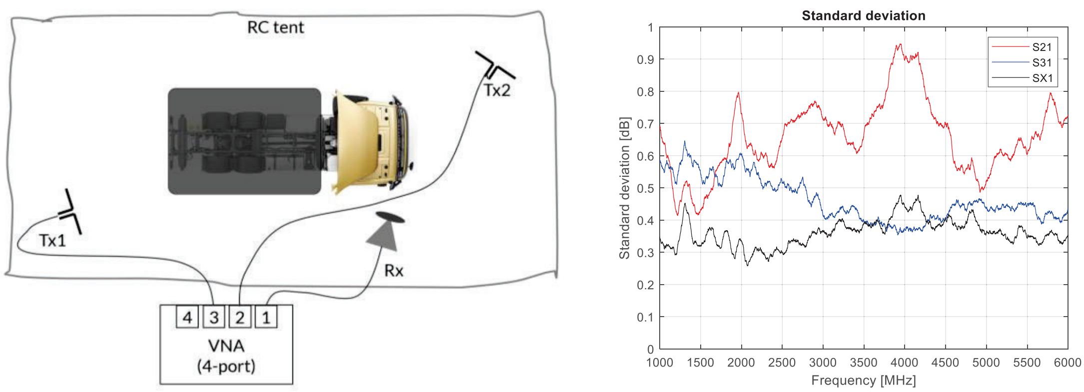

Figure 10. Measurement setup (left) and standard deviation (right) of individual Tx to Rx sets (s_{21}, or s_{31}), and the combination of the two $\left((s_{21} + s_{31})/\sqrt{2}\right)$.

Test zones:

A cavity in a vehicle is a constrained volume within the vehicular structure, e.g., the trunk, an open space in the engine compartment, a wheelhouse, etc. A cavity can contain electronic hardware (like ECUs), possibly susceptible to incoming electromagnetic (EM) fields. In **D2B.1**, we investigate the properties of cavities, how they are excited, shielding, and statistical properties.

During EMC immunity test the cavities can be excited through one or several apertures, and the excitation depends on the EMC test method. It is also possible that a second cavity is excited via a first cavity etc. It should be noted that the cavities are equal during tests in an RC or in, e.g., a semi-anechoic chamber – it is the aperture excitations that differ.

Any given cavity will have a cut-off frequency of its first resonance (mode) from which it can be excited (its first eigenmode). For frequencies lower than that frequency, the field that is built up in the cavity will be significantly reduced, evanescent, compared to a supported mode (resonant frequency). However, in a vehicular cavity, apertures might be both multiple and large and thereby allowing some energy to propagate and somewhat lessen the suppression of the field below the first eigenmode. For higher-order modes many vehicular cavities will also have a LUF like the RC, a "cavity LUF", above which the field to some extent will fulfil the requirements of RC LUF due to its excitations through apertures in combination with varying incoming fields in the stirred RC, or in the dynamic real world. An aperture can be a hole, a slit, a penetrating wire, or another mechanism of arbitrary shape allowing EM fields to transmit through an interface from one region to another.

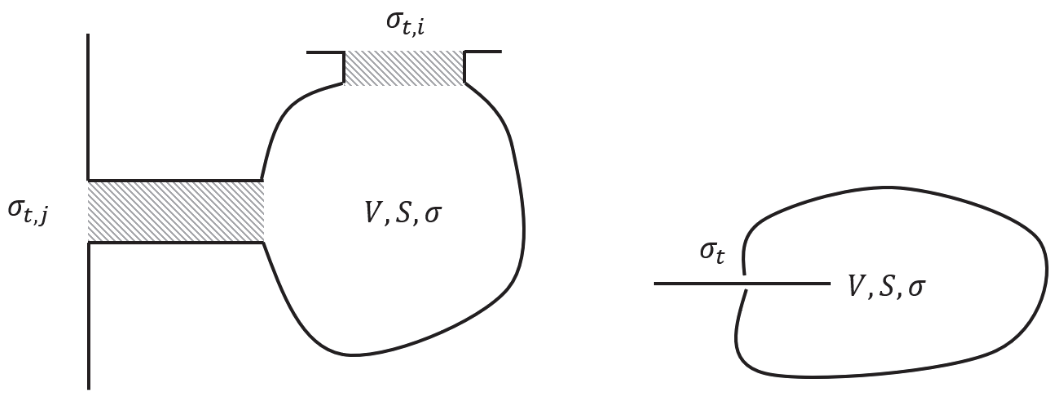

Figure 11. Left: a cavity with two apertures (grey). Right: A cavity punctuated by conductive wire.

Most vehicular cavities are static in their geometry and material, such as the trunk. Some cavities however, like the wheelhouses when the vehicle is tested in active mode on the dynamometer or in real operation, there will be inherent mode-stirring due to moving parts. At least above some frequency.

The total electric field magnitude can be measured and, its statistical distribution, related to the χ-distribution and thereby quantifying the underlying Degrees of Freedom (DoF). It can then serve as a tool to categorize regimes of cavity responses.

A short description of the distributions starts with that a Gaussian distribution is a natural consequence of stochastic systems and large numbers. For that reason, a complex-valued field variable, such as an electric field component phasor will follow the standard complex normal distribution in an RC (above LUF). The magnitude of such a phasor, i.e., a component of the electric field, will then follow a Rayleigh distribution. The concept can be extended to field variables with higher underlying dimensionality, such as the total electric field magnitude, by the χ-distribution. The square of the total electric field will then be χ_2-distributed. An ergodic field is isotropic and uniform and in three dimensions the total electric field magnitude in an RC follows χ-distribution with six DoF; amplitude and phase for each of the three electric field components. If electric field components are correlated the DoF reduces. It can be noted that most antennas only pick up one electric field component and the method then requires measuring three linearly independent components simultaneously, which can be accomplished using a three-axis field probe.

A three-axis field probe was used to collect data and three characterization methods for the distribution within a cavity were proposed and evaluated by the project: standard deviation, correlation and estimation of DoF. In this report we give an example of the latter.

Estimation of DoF of the χ-distributed total electrical field magnitudes is performed by comparing the distributions of the data, both of individual field components as well as total field, to their theoretical χ-distributions. Results are shown in Figure 12 and shows how the DoF at low frequencies are reduced to approximately two, and then spans all the way up to six DoF at 1000 MHz. This method has also been published in IEEE conference EMC Europe [2].

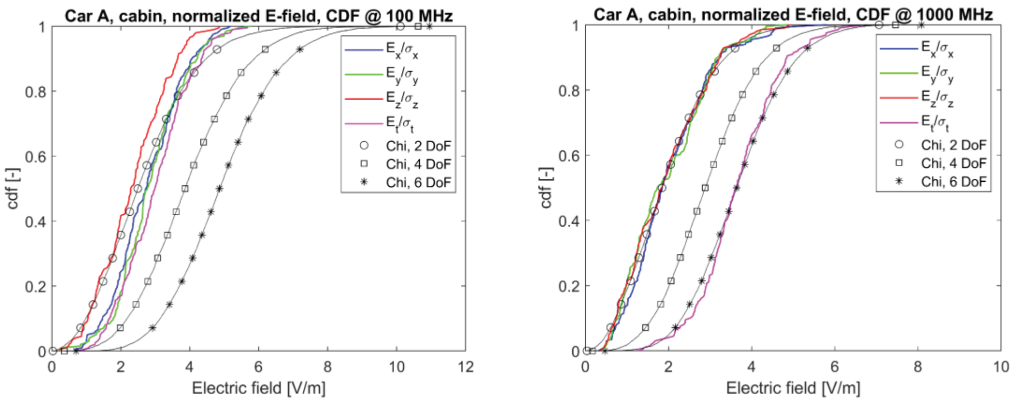

Figure 12. CDF of normalized electrical field sampled in the cabin of car A. Left: at 100 MHz the total electrical field magnitude is χ-distributed with less than two DoF. Right: The total electrical field magnitude is χ-distributed with approximately six DoF.

The shielding, or relative loss, compared to a reference position outside the vehicle was also measured. This was done either with an electrical field probe, or by wideband power sweep with the VNA. Measurements were performed for both a car and a truck. Examples of the results can be seen in Figure 13-Figure 15, where some variation can be seen both over position as well as frequency.

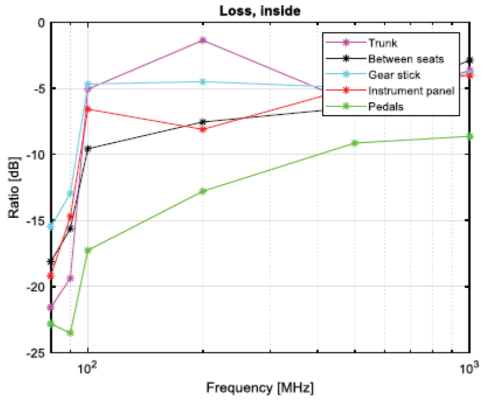

Figure 13. Field into trunk and different positions in car cabin. Mean total electrical field in specific position normalized with mean total electrical field in reference position outside vehicle.

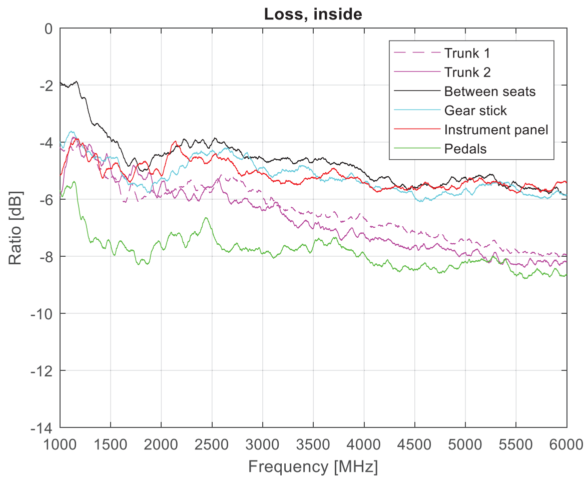

Figure 14. Field into trunk and different positions in car cabin.

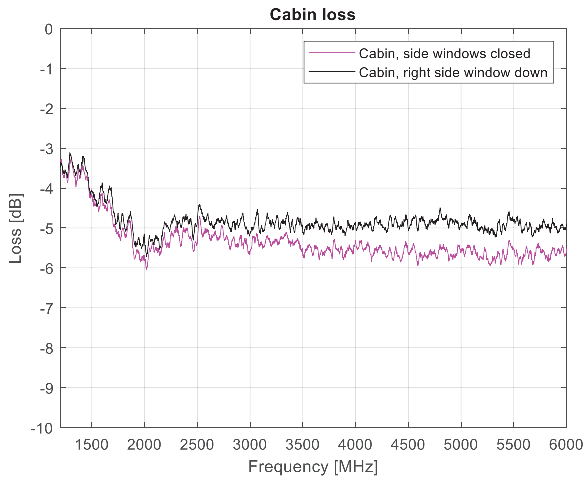

Figure 15. Field into truck cabin. Windows closed, or right-side window open.

In addition to the above the project has also investigated the use of Q-value measurements in RCs to estimate the average loss in, first, the RC tent, and secondly, in a vehicle to be investigated by simulations. The second step applies a generic loss model on the vehicle metallic surfaces and thereby "calibrates" the electromagnetic simulation model. The losses are modelled by very thin sheets with low conductivity in comparison to normal metals. The method has been described, validated, and used to simulate electrical fields in vehicles and vehicular cavities. The method is submitted to IEEE Transactions on Electromagnetic Compatibility [4].

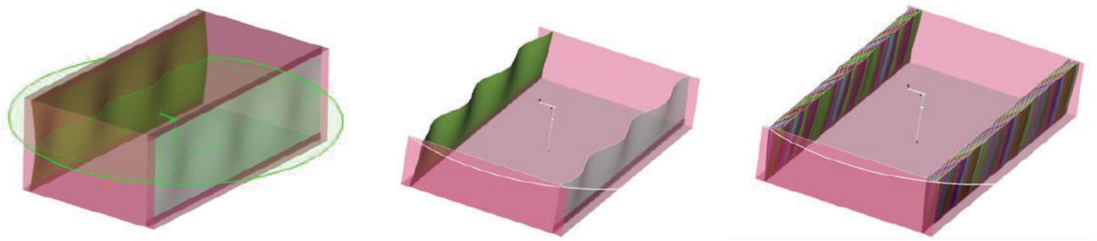

Figure 16. Visual representation of the VIRC simulation domain and model of the moving walls used in [4]. (a) One wall configuration. (b) Using a horizontal clip plane. (c) Showing all wall configurations at once.

1.3 WP2C – Novel method for on-board unit test

WP2C	**Novel method for on-board unit test**
Description:	OBT is performed in the frequency range 1.8MHz – 6GHz. Define methods in the higher end of that spectrum to characterize the temporarily created RC, and methods to perform a RC based OBT test. After the definition of characterization and test methods, tests will be performed and validate against the standard OBT test performed in ALSE. Evaluate the method and test with regards to, e.g., test time and test confidence.
Deliverables:	D2C.1. Specific equipment for versatile mode stirring. D2C.2. Report describing the novel OBT test setup, including characterization, measurement results, and validation.

WP2C investigates the possibility to use a certain VUT compartment, or cabin, as a temporary RC and apply On-Board Transmitter (OBT) test within that compartment. Until now, OBT is performed by an "old school" method with some known drawbacks such as measurement accuracy due to antenna impedance mismatch (due to near-field effects) and very long test times. The hypothesis is that, by constructing a metallic cavity within the vehicle, e.g., by wrapping the vehicle in a conductive textile and adding portable mode stirrers inside, a temporary RC can be created and validated, and tests can be performed; more efficient and with better accuracy compared to the standard OBT method.

Normally, OBT tests are performed in the frequency range 26 MHz – 6 GHz. In this work we focused on the higher end of that frequency spectrum. An attempt has been made to define a method to perform a RC based OBT test. we choose to name this novel test method as Reverberating On-Board Transmitter (ROBT).

The version of the method, explored within this project, places the VUT on a sheet of conductive textile, like the one constituting the walls, floor, and ceiling of the VIRC (Figure 17). Another sheet of the same material is then used to cover the VUT and the joint between the two sheets is sealed by placing weighted tubes around the entire VUT, thus ensuring a good electrical contact.

Figure 17. VUT covered by conductive textile sheets for ROBT testing. A probe is here placed outside the VUT for shielding verification measurements.

The conventional OBT test method, per ISO 11451-3 [5], is recommended to be performed in a semi anechoic chamber. In this study, the method will be addressed for OBT-testing inside the vehicle (the standard advocates OBT testing either inside and/or outside the vehicle). The standard recommends at least to place the OBT antenna at the driver's head position, at the passenger's head position, at the rear passenger's head position and in specified places where a portable transmitter can be placed. There may also be other positions of interest. This test may be time consuming with respect to the number of test positions of the OBT antenna as well as the different service bands being tested. Therefore, it would be desirable to benefit from the advantages of using an RC environment, e.g., transforming the vehicle to a temporarily RC by wrapping the vehicle in a conductive textile and adding portable mode stirrers inside, i.e., the ROBT method. Assuming the mode stirring is good enough, the electric field inside the vehicle will be randomly polarized, isotropic and after some time even homogenous. In this proposed test environment, all possible OBT antenna positions will be tested at the same time.

The ROBT method should preferably be possible to perform outside a separate shielded enclosure. For personal safety as well as for complying to electromagnetic spectrum regulations the shielding of the vehicle, when wrapped in conductive textile, was first evaluated and determined to be satisfactory.

[5] ISO 11451-3:2015 Road vehicles — Vehicle test methods for electrical disturbances from narrowband radiated electromagnetic energy — Part 3: On-board transmitter simulation, 2015.

The method, developed in the project, included several improvements to attain sufficient mode stirring:

1. Two stirrers of different shape and rotating speed, which were operational inside the VUT (Figure 18 and Figure 19).
2. Maximizing the free volume of the VUT, by, e.g., reclining the seats.
3. An antenna rotator for improved variation in (mainly) polarization (Figure 19).

It is also recommended to direct the transmitting antenna into one of the stirrers for good mode stirring.

Figure 18. Left: Overview of ROBT stirrers: (1) clockwise mode stirrer, (2) counterclockwise mode stirrer, (3) Tx antenna placed on oscillating stand. Right: Continuously clockwise rotating stirrer (1) placed in front passenger seat.

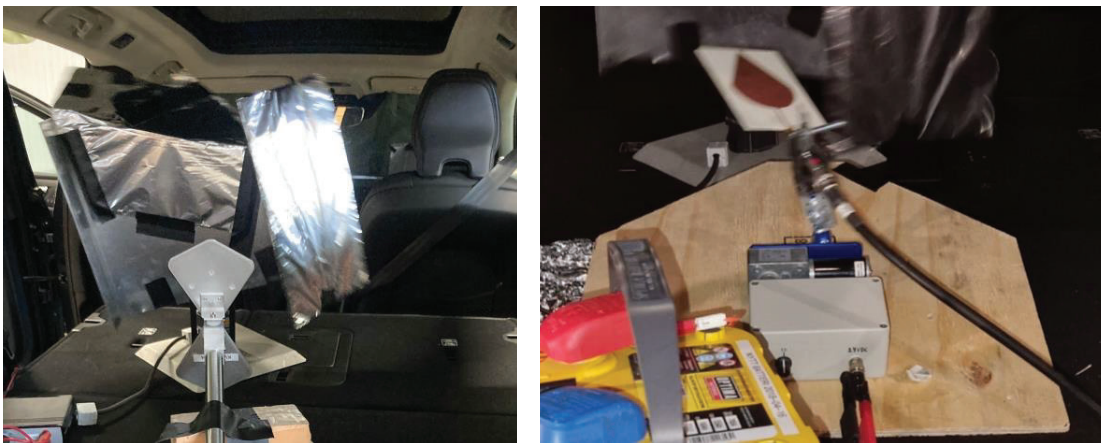

Figure 19. Left: Counterclockwise stirrer placed in trunk (2). Right: Antenna oscillator. Oscillating the antenna back and forth from the left to the right (3).

Two new measures were developed for evaluation of the RC statistics of the likely non-ideal environment of the ROBT setup. These are termed isotropicity, and $\Delta\chi$. The two new measures complement each other in that isotropicity is used to evaluate if the average level of the field is similar for all polarizations, and $\Delta\chi_{6-2}$ to then estimate the total DoF.

For the evaluation of the ROBT, using these two new measures, a three-axis field probe was used to collect data.

Isotropicity is defined as:

$$e_{iso} = \frac{\max(\langle E_x\rangle, \langle E_y\rangle, \langle E_z\rangle) - \min(\langle E_x\rangle, \langle E_y\rangle, \langle E_z\rangle)}{\langle\langle E_x\rangle, \langle E_y\rangle, \langle E_z\rangle\rangle}$$

This expression is evaluated per frequency and has a minimum of zero (perfect isotropic fields) and a maximum of three (only field in one of the x, y, or z components): $e_{iso} \in [0,3]$.

Figure 20 shows the effects of the improved stirring on the isotropicity measure. Looking at the average over all evaluated frequencies it becomes clear that the measure successively decreases. It remains to be determined if further improvements of the stirring is needed.

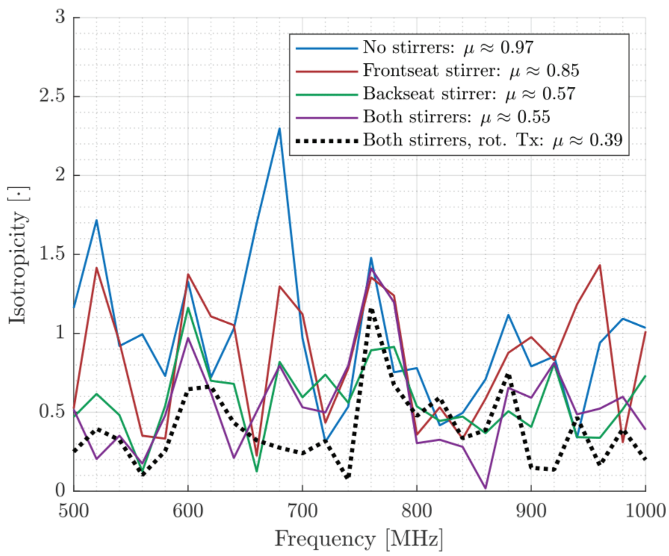

Figure 20. Isotropicity over frequency for different stirrer settings. Figure from [5].

Assuming the field has been determined to be isotropic in amplitude to a satisfactory level, $\Delta\chi$ inspects the difference between the median of the total field and the field components. As is mentioned in WP2B the individual field components and total field should follow χ-distributions with two and six DoF respectively. These ideal χ-distributions are known and the difference between the median of each, in the normalized case, can be calculated (see Figure 21).

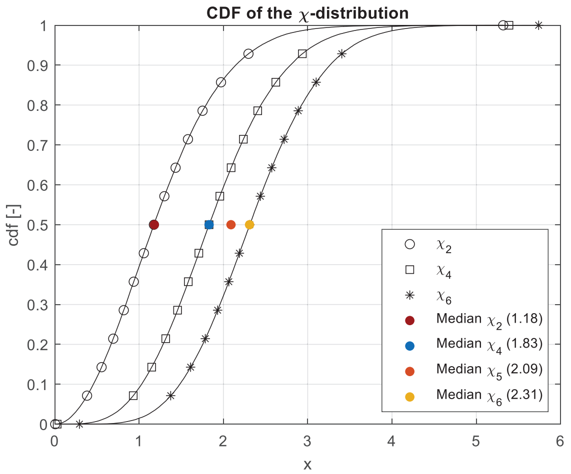

Figure 21. CDF of some selected χ_n-distributions with corresponding medians.

$\Delta\chi$ is calculated in three steps:

1. by assuming the samples over all three polarizations together are also χ-distributed with two DoF, they are normalized by their collective mean.
2. from that the total E-field is calculated.
3. Difference between the median of the total E-field and the largest median of the three polarizations is calculated.

With higher number of DoF the value should then approach $\Delta\chi_{6-2}$. We have set an acceptance level of Δχ above $\Delta\chi_{5-2}$. Figure 22 shows how the DoF increases with frequency.

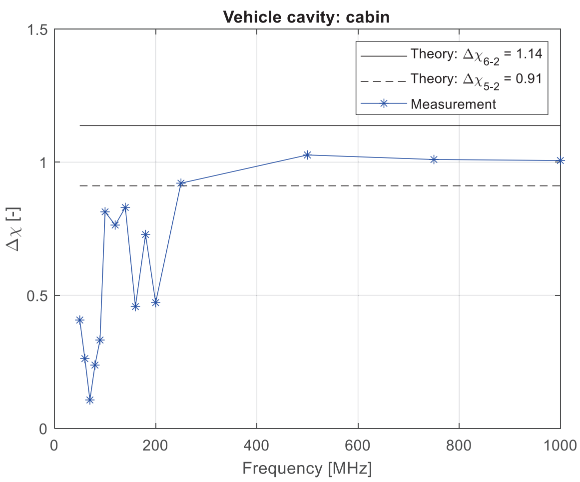

Figure 22. Δχ close to the centre stack in a vehicle cabin. The cavity fulfils the stringent criterion from approximately 250 MHz.

During an immunity test with the ROBT the goal is to have the same test levels as described in OBT procedures. Therefore, a correction factor how to convert from OBT to ROBT is needed. We here suggest a correction factor based on measurements in a reference vehicle, which can then be transferred to any other test vehicle. In the reference vehicle an electric field probe was placed in a position, behind a panel in a vehicle, representative of where one would typically find an ECU or similar (compare Figure 28). The total field was then measured using first an OBT antenna, in its typical position, and secondly the ROBT antenna placed as it would in a ROBT test, giving:

$$C_0 = \frac{\langle E_{t,OBT,ref}^2 \rangle}{\langle E_{t,ROBT,ref}^2 \rangle}$$

The ROBT transfer function G_{ROBT} should be measured for both the reference vehicle as well as the test vehicle. This together with the total radiation efficiency η of the OBT and the ROBT antennae respectively gives the correction factor:

$$C_{test} = C_0 \cdot \frac{G_{ROBT,ref}}{G_{ROBT,test}} \cdot \frac{\eta_{OBT}}{\eta_{ROBT}}$$

Which then only demands the transfer function be determined for a new test vehicle to determine the proper correction factor. From this it is thus possible to calculate that the proper output power during ROBT testing should be:

$$P_{ROBT} = P_{OBT} \cdot C_{test} \; [W]$$

Where P_{OBT} is the output power specified in the standard.

The ROBT method was evaluated by looking at isotropicity, Δχ, field uniformity, as well as an attempt at a direct comparison with the OBT method.

Results in Figure 23 and Figure 24 below show quite good isotropicity as well as Δ_χ (when compared to the less stringent requirement).

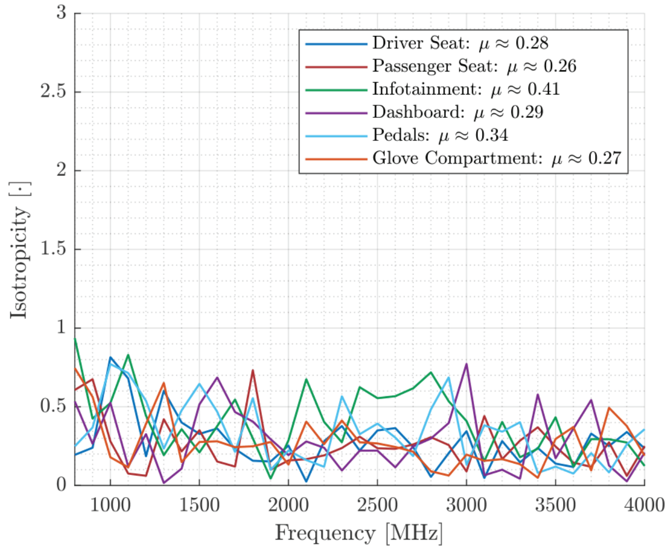

Figure 23. Isotropicity in different positions. Figure from [5].

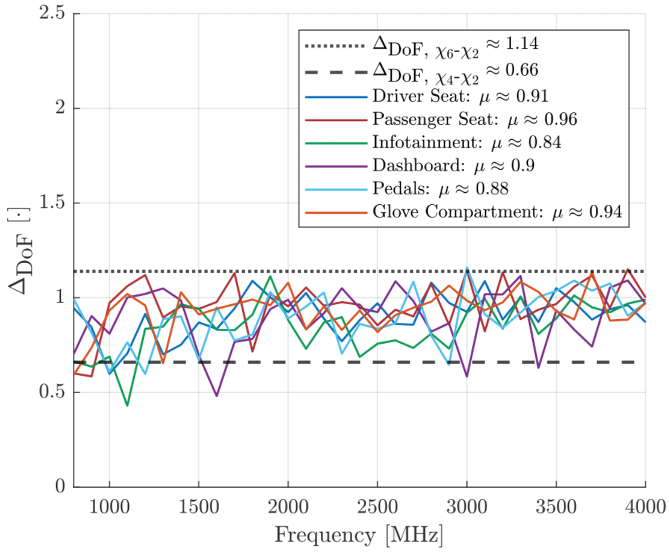

Figure 24. Δ_χ in different positions. Figure from [5].

The collected data in the six different positions (examples in Figure 25) was also used for evaluation of field uniformity. Results in Figure 26 shows that open positions closer to the Tx antenna, such as *Infotainment* or *Passenger seat* will get higher fields on average, compared to tighter positions further away from the Tx antenna like *Pedals* and *Glove compartment,* and the ROBT method is thus not a perfect RC. Figure 27 however shows how a comparison between the field strength standard deviation of the six ROBT positions to that of six OBT Tx antenna positions to one field probe position (Figure 28) reveals that the ROBT method can be considered more accurate than the standard OBT method. This is not an exact comparison but still a good indication of how they relate to each other in terms of measurement uncertainty.

Figure 25. Two of the tested positions. Pedals and Dashboard.

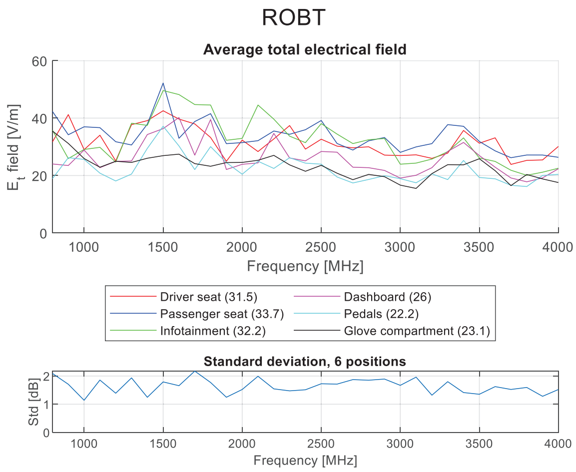

Figure 26. Average total electrical field in six different positions and standard deviation between these six datasets. Numbers in parenthesis are average values per position.

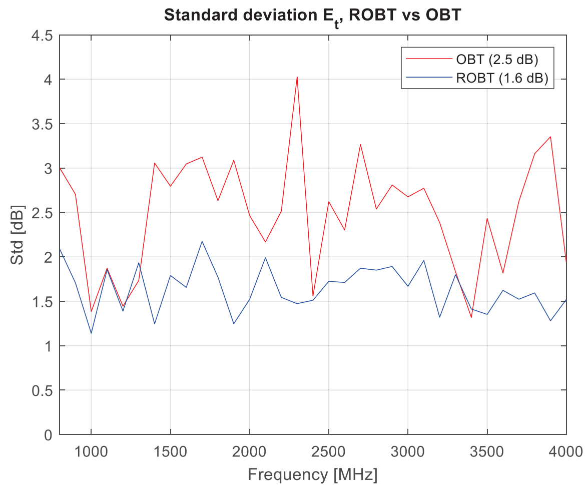

Figure 27. Standard deviation for the ROBT vs the standard OBT method. Averages in parentheses.

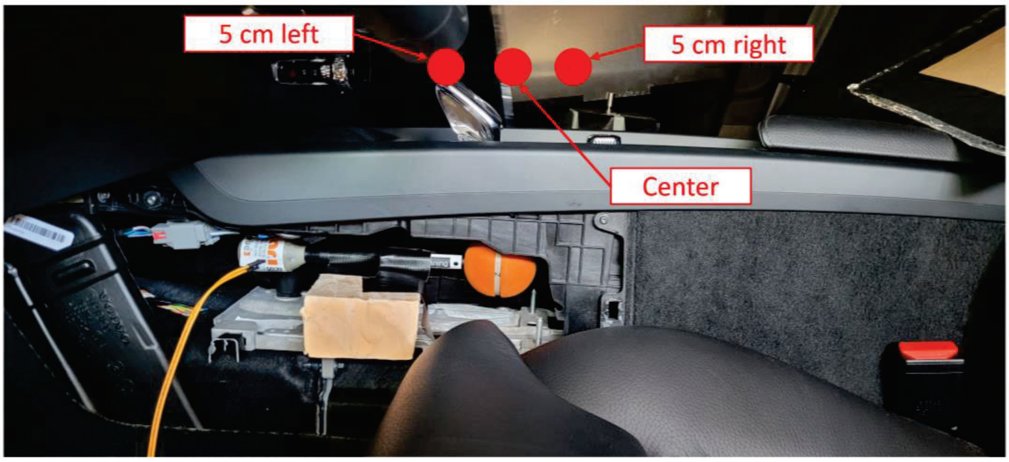

Figure 28. Positions of the OBT antenna. All three positions were tested in V-pol (antenna elements parallel to driving direction of vehicle) and H-pol (antenna elements perpendicular to driving direction of vehicle).

The ROBT method was not able to deliver mode stirring on par with the demands for a RC, due to the limited space in a vehicle etc. However, it still delivers better results than the standard OBT methods in terms of repeatability and accuracy. It is also faster and more comprehensive, than the standard OBT method, as it tests all positions and polarisations at once.

The ROBT method carries the advantage, compared to RC, that the transmitter is located inside the VUT, and it requires less input power, lowering the risk of over-testing the outside of the VUT when trying to reach sufficient levels for testing the inside. Another advantage is that the ROBT method does not need a complete RC, making a less space consuming set-up possible.

1.4 WP3 – EMC test realization

WP 3	**EMC test realization**
Description:	For a specific test object: perform EMC test according to standardized methods in ALSE as well as with the proposed method in RC. We aim to perform the comparison for a set of test vehicles (both cars and trucks) to gain statistical confidence in the conclusions. This means that a lot of EMC testing will be performed and included in the analysis.
Deliverables:	D3.1 Report on comparisons between RC and ALSE EMC test results.

Important for the user of the method is to understand if testing with the new standardized RC method, ISO 11451-5, gives the same result as testing in an ALSE, ISO 11451. Four test campaigns with different passenger vehicles and trucks have been performed during the project.

The result from the testing of passenger cars showed that more interferences were found in the VIRC compared to standard testing in ALSE. The additional interferences found could be reproduced in ALSE by testing other angles of irradiation or other polarizations then normally tested. There were no interferences found in the ALSE that were not detected in the VIRC.

1.5 WP4 – Dissemination and Demonstration

WP 4	**Dissemination and Demonstration**
Description:	The project will be visible in selected media channels. Presentations at conferences (e.g., EMC Europe or Vinnova FFI conference). Publication of two conference papers (e.g., EMC Europe). Contribute to ISO WD/ISO 11451-5. The achievements and benefits of the methods developed in the project will be demonstrated at a final presentation.
Deliverables:	D4.1 Close collaboration with ISO regarding standardization of RC methods for road vehicles (several partners are members). D4.2 A demonstration with participants from related industries. D4.3 At least two research publications.

The project has compiled and proposed a method, the power average method, to the ISO working group ISO/TC 22/SC 32/WG 3 “Electromagnetic compatibility” during the update of ISO 11451-5. After voting the method was accepted as an informative Annex (Annex I). The standard was released during 2023.

The complete test method developed during the project, as well as other project results, were demonstrated April 25, 2023, at RISE in Borås with invited participants from Swedish industry and Academia, see Figure 29.

In section 7.2 in this report the external research publications are listed.

Figure 29. Photo from a presentation of project results at the EMCVERA demo.

Dissemination and publications

1.6 Dissemination

How are the project results planned to be used and disseminated?	Mark with X	Comment
Increase knowledge in the field	X	Aside from the direct experience the project participants have gained during the work, knowledge have been shared by contributing to the ISO standardization of the method, presentation at conference and organizing seminar and demo of the method.
Be passed on to other advanced technological development projects		
Be passed on to product development projects	X	Method can be beneficial to use to secure EMC in vehicles.
Introduced on the market	X	Method will be offered by the test institutes used by automotive industry during development of new vehicles.
Used in investigations / regulatory / licensing / political decisions		

1.7 Publications

[1] Kalaran Hans, Karlsson, Kristian, Moestam Robert, Bergqvist Björn and Rosdalen Åsa, ”Eigenmodes of a Loaded Reverberation Chamber” EMC Europe, 5-8 September, 2022, 2022, Göteborg, Sweden.

[2] Karlsson, Kristian, Moestam Robert, Bergqvist Björn, Rosdalen Åsa and Kalaran Hans, ”Electrical Fields in Vehicular Cavities During Reverberation Chamber EMC Immunity Test” EMC Europe, 5-8 September, 2022, 2022, Göteborg, Sweden.

[3] Karlsson Kristian, Lundberg Andreas, Arabäck Niklas and Bergqvist Björn, ”Test level in Reverberation Chamber EMC Immunity Assessment Based on the Quantile to Average Ratio“ EMC Europe, 5-8 September, 2022, 2022, Göteborg, Sweden.

[4] Moestam Robert and Karlsson Kristian, “Numerical modelling of EMC immunity tests in vibrating intrinsic reverberation chambers and thereby improving simulation model for vehicles in anechoic chambers,” submitted to IEEE Transactions on Electromagnetic Compatibility, June, 2023.

[5] Holm Ludvig, ”Development of a Novel Method for Automotive Onboard Transmitter EMC Immunity Testing,” Master thesis, Uppsala University, UPTEC F 23018, 2023.

Conclusions and future research

The project has been successful in establishing a reliable and repeatable method for EMC immunity test of full-sized vehicles like cars and trucks. In the project we have also addressed one of the limitations for RCs (or VIRCs), the LUF, which is mainly set by the dimensions of the test chamber (given well designed stirrers).

In order to adhere to the lower frequency requirement of 20 to 30 MHz, as mandated by EMC immunity standards[6], an RC would need to be colossal, with dimensions approximately 40 meters in length, 20 meters in width, and 15 meters in height. However, even if such an enormous RC were to be constructed, it would give rise to another challenge: the substantial power requirements and the consequent high costs associated with its investment (RF amplifiers!) and operation. Recent advancements have proposed an alternative approach to utilize the RC below the LUF. In essence, it will function as a shielded metallic room with one or a few electromagnetic cavity modes, as pioneered by companies like Daimler[7], and recently released in ISO 11451-5:2023. But more investigations are needed. Ongoing research and development in this field show promising results for achieving a comprehensive frequency coverage test range. This innovative approach not only ensures cost-efficiency but also enhances the reliability of EMC immunity tests, even at frequencies below the LUF, extending all the way down to 30 MHz.

EMC emissions test of full-sized vehicles. Today CISPR 12 is used, which applies to vehicles, boats, and internal combustion engines. The limits are designed to provide protection for receivers in the frequency range of 30 - 1000 MHz when used in residential environment. Just as in the case of an EMC immunity test, a test in RC would be beneficial in terms of test efficiency and reliability. The RC is expected to detect disturbances independent of the angle, and polarization, step size of the measurement antenna. This is especially important for any extension of the upper frequency limit as emission patterns in general are increasingly complex for higher frequencies.

In accordance with the first section in this chapter, emission measurements below RC LUF can also be investigated, exploring if a comprehensive frequency coverage test range for emissions can be established.

The ROBT method showed promising results in terms of, once again, test efficiency and repeatability. It is also inherently good in applying fields to all ECUs with all polarizations and angles. This work has not yet been published and, of course, remains to, if possible, implement in and standard.

Finally, one of the project aims was EMC validation of autonomous vehicles. This is still a complex task as the vehicles sensors are rapidly developing in terms of sensitivity, quantity, complexity, and functionality, driven by the global industry and their aims for

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[6] ISO 11451-2:2015

[7] https://group.mercedes-benz.com/innovation/case/connectivity/opening-testing-facility-for-emc.html

efficient vehicles with everything from Advanced Driver Assistance Systems (ADAS) to Autonomous Drive (AD) functions. This is an area where there is room for essentially more work after this project. Both local work as well as international cooperation in addressing these challenges.

Participating parties and contact persons

Partners in the project have ben:

Volvo Car Corporation	(556074-3089)
CEVT AB	(556922-7639)
Volvo Technology AB	(556542-4321)
RISE Research Institutes of Sweden (RISE)	(556464-6874)

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