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Electromagnetic emissions assessment of a fuel cell electric vehicle in dynamic driving conditions

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Abstract

Vehicles commercial market is growing fast and new technologies are entering the market in order to reduce pollutant emissions and ensure a green driving experience. In order to assess potential benefits brought by the electrification of transport, it becomes more and more important to evaluate the performance of all kinds of electrified vehicles in terms of electromagnetic emissions in real-driving conditions.

This technical report shows the main outcomes of a test campaign conducted on a Hyundai Nexo (fuel cell vehicle) within VeLA 9 laboratory. The vehicle was tested under more realistic driving conditions beyond the requirements of UNECE Regulation n.10 to check its performances in terms of radiated emissions with regard to electromagnetic compatibility. Other tests were conducted beyond the Regulation in order to assess possible improvements on the current measurement procedures.

Showing the impact of different speeds, driving cycles, driving modes and measuring setup on electromagnetic emissions was evaluated as well as broad frequency ranges were explored.

1 Introduction

Fuel cell electric vehicles (FCEV) are not anymore a pipedream, indeed they are a commercial reality. Different brands and vehicle models are now available for general public usage. FCEVs are classified as zero-emission vehicles as they are full-fledged electric drive systems and they emit only water and heat. The fuel cell is used to power the electric motor, a small energy storage system such as battery or super capacitor is always present to permit the recovery of regenerative braking energy and it supports the response to the driving demand during acceleration. A fuel cell is an electrochemical system that converts oxygen and hydrogen to electric energy, heat and water. Several types of fuel cells are available but for road mobility applications the most used is the proton exchange membrane type (PEM) because it is characterized by a good compromise among power density, efficiency, low working temperature, weight and cost.

Being a new technology on the market, there are few data available about the performances of such vehicles, especially from the electromagnetic compatibility point of view. Of course, to be released on the market, they should be tested and approved according to UNECE Regulation n.10, which establishes the compliance of the vehicle against the EMC standards. The assessment of radiated broadband emissions generated by the vehicle is a paramount part of that Regulation and it is the core element of this test campaign. The characterization of the electric and magnetic field (EMF) environment produced by the vehicle during driving is challenging due to its complexity and its variability in time, space and frequency. However, tests in more realistic conditions are rare and, consequently, valuable from a scientific perspective. Technical reports showing data from experimental test campaigns aim to consolidate the robustness of the scientific studies. What it is more, they contribute to increase the confidence in the reliability and the safety of these new products.

The Sustainable Transport Unit of the European Commission's Joint Research Centre (JRC) carries on its commitment in order to acquire expertise and experimental knowledge in terms of EMC behaviour of all new vehicles technologies. The test campaign object of this report was conducted in the semi anechoic chamber Vela 9 and involved a sample of FCEV Hyundai Nexo. This is to be added to all the other publications of the JRC Vela 9 team regarding radiated emissions coming from vehicles where different technologies are in place (Pliakostathis et al., 2020; Pliakostathis et al., 2018; Pliakostathis, 2019; Pliakostathis et al., 2019).

Regardless of the technology, any possible interference should be avoided and the electro-magnetic compatibility should be guaranteed. Sources of radiated emissions can be several: cables, electronic modules and engines, batteries and their chargers, accessories and many others. However, the identification of the sources is out of the main scope of this work. This task is primarily left to the industry, to its quality, design and testing engineers.

The scope of our test campaign is to navigate among strengths and limits of the test method foreseen by the actual in-use Regulation, and to explore new measurement scenarios, that are more faithful to the real use cases.

Different constant speeds as well as stepped cycles with strong accelerations were considered. The investigation covered also the impact of different driving modes of the vehicle. All vehicle testing positions (front, rear, left and right) compared to the tip of the antenna were taken into account, in order to spatially characterize the produced EMF. Broad range of frequencies were analysed going beyond the ones indicated by the Regulation n.10. Once identified the most potential critical frequencies, specific time domain analysis were conducted in order to deeply characterize the radiated emissions.

2 Vehicle overview

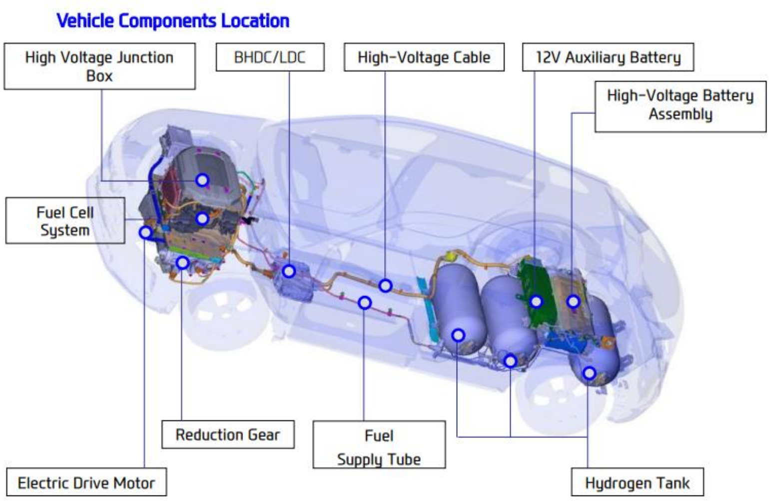
The equipment under test (EuT) is the Hyundai Nexo (2019), a front wheel drive fuel cell electric vehicle available on the European market.

The powertrain of the vehicle has a mild hybrid configuration with a fuel cell stack and a high voltage battery pack in support feeding a traction electric motor coupled with a single-speed transmission box (reduction gear). The presence of the battery pack allows the energy braking recuperation and the storage of extra energy production from the stack during power request transition, moreover it consents a prompt response to the driving power demand. The fuel cell stack is composed by several hydrogen PEM (Proton Exchange Membrane) cells, it has a maximum power output of 95 kW and its power density is 3.1 kW/l, the delivered voltage range is 240-450 V. The stack is fed with pure hydrogen through a pipeline from the 3 hydrogen tanks. The total hydrogen storage capacity is 156.6 litres at 70 MPa maximum pressure (6.3 kg at 100% state of charge) with a full refuelling expected time around 3 to 5 minutes. The battery pack is a Lithium-ion Polymer type; it consists of 64 cells each one sealed in an aluminium case to protect against electrolyte spillage and boxed together in an aluminium enclosing. The high voltage battery pack has a rated maximum power of 240 V and it has a capacity of 6.5 Ah and energy storage up to 156 kWh. The electric motor is a permanent magnet synchronous motor and it has a maximum power of 120 kW (161 hp) and a maximum torque of 395 Nm. Others core components of the system are:

- an AC/DC bidirectional inverter that transforms the direct current to alternate current to feed the motor and vice versa to produce the regenerative braking energy to charge the battery,
- a high voltage battery DC converter (BHDC) that converts the voltage among high voltage battery,
- the fuel cell stack and inverter,
- a low voltage converter (LDC) converting to low voltage (12V) to charge the service battery,
- a high voltage junction box which distributes the energy from the battery and the stack to the inverter and the others high voltage components (e.g. air compressor, coolant pump, etc).

Figure 1 shows the location of vehicle components.

Figure 1. Vehicle components location



Source: NEXO emergency response guide.

2.1 Driving Modes

Three driving modes are available (see Table 1). Depending on the selection, the driving mode affects power curve and auxiliaries such as climate control in order to maximise efficiency.

The vehicle has also three different levels of the regenerative braking capacity that regulate the power of the deceleration produced at the pedal release and consequently produce more or less regenerative braking energy.

Table 1. Hyundai Nexo driving modes

COMFORT	Uses the power available giving priority to the driving comfort. If the vehicle is settled to this status at the power off it will remain selected at the restart.
ECO	Optimizes battery charging use efficiency. In this mode acceleration may be slightly reduced when the pedal is pressed moderately and the air conditioner performances are limited. If the vehicle is settled to this status at the power off it will remain selected at the restart.
ECO +	Maximises fuel efficiency reducing energy consumption with saving strategies such as turning off the air conditioner and limiting the maximum vehicle speed to 100 km/h.

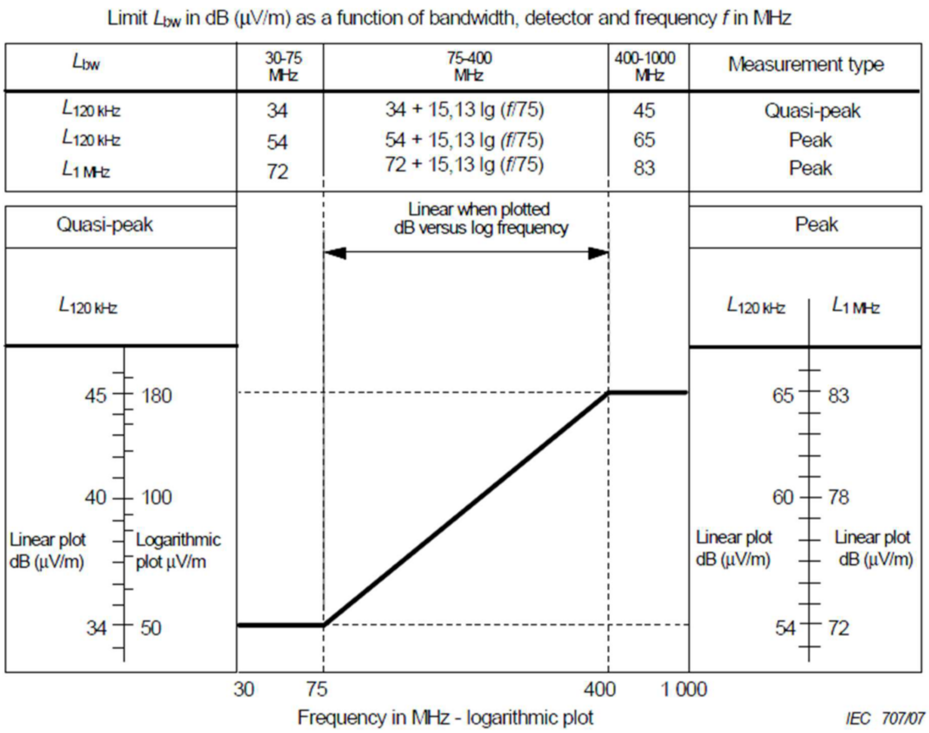
Source: JRC, 2021.

3 Normative framework

UNECE Regulation n.10 regulates Electromagnetic compatibility (EMC) within the automotive sector (UNECE, 2012). Among several requirements, it addresses unwanted radiated and conducted emissions issues as well as the immunity to radiated and conducted disturbances in order to protect other road users, adjacent vehicles and equipment as well as the vehicle, the driver and passengers.

According to the Regulation, only the left and right sides of the vehicle need to be tested for broadband radiated emissions (RE) over the frequency range of 30 to 1000MHz. The vehicle must to be driven at a constant speed of 40km/h (or the maximum speed if this is below 40km/h) and in idle mode (with Key-On, Engine-Off) for narrowband radiated emission (RE). The antenna used for the measurement can be fixed at either 3m height and, 10m distance from the car or at 1.8m height and 3m distance from the car. Furthermore, both horizontal and vertical polarizations have to be tested for both sides of the vehicle. Figure 2 reports limits for radiated emissions established by the international standard CISPR12 and in-use within Regulation n.10. If a 3m distance is used, 10dB increase in the limits should be considered.

Figure 2. CISPR 12 limits for radiated emissions within the frequency range 30 MHz – 1000MHz.



Source: IEC, CISPR12 (IEC, 2001).

In order to overcome some limitations of the Regulation, several constant speeds were considered (40, 60, 80, 100, 120 km/h) as well as customized driving cycles (stepped accelerations: 0-40-60-80-100-120-0 km/h). Regarding the vehicle positioning, all side of the vehicle were included in the test protocol and the turntable was used to perform 360 degrees rotations in order to check emissions from all possible directions. The reason for the introduction of these new tests requirements is to consider the effect of new vehicles architectures and technologies (hybrid, electric and fuel cell vehicles) and to investigate all vehicle operating conditions. Furthermore, broader frequency ranges were explored in order to find out possible disturbances generated by electric powertrains and other new technologies and ancillaries.

4 Test set up

4.1 Test facility

VeLA 9 is one of the laboratories of the Joint Research Centre sited in Ispra, Italy and it belongs to the Sustainable Transport Unit. The test campaign was performed between the 12^{nd} and the 22^{nd} January 2021 and between the 12^{nd} and the 16^{th} July 2021. The laboratory is a semi-anechoic chamber equipped with a 4-wheel chassis dynamometer built on a turntable of a diameter of 11 m that can rotate 360 degrees. This system can reach up to 200 km/h with acceleration and deceleration values up to ±10 m/s^2. During the test campaign, the chamber was kept at a temperature of 23 °C ±3 °C with a relative humidity of 55%.

4.2 Electrical Instrumentation Layout

The test campaign was executed with the following laboratory equipment:

- EMI Test Receiver: Rohde & Schwarz model ESR7. This instrument operates within the frequency range 9 kHz - 7 GHz and it is compliant with the CISPR 16-1-1 standard. It is able to measure electromagnetic disturbances with the stepped frequency scan or with an FFT-based time domain scan at an extremely high speed. It performs real-time spectrum analysis, and it allows displaying data in the time domain with high resolution (50 μs) by means of an integrated oscilloscope function. It offers the possibility to customize transducer sets, to configure pre-set antenna factors as well as EMI limits of commercial standards (Rohde & Schwarz Systems Support Center).

- VULB 9162 Antenna SCHWARZBECK MESS – ELEKTRONIK. This antenna is a linear polarized logarithmic periodic broadband antenna combined with a 4:1 broadband dipole (Aluminium tubing) used for receive and transmit applications within the frequency range 30 MHz – 7 GHz (Schwarzbeck Mess-Elektronik).

- ETS-Lindgren's Model 3301C. This instrument is an active Monopole Antenna able to receive an electric field in a single band 30 Hz – 50MHz. It is characterized by a wide dynamic range (141dB), and it is able to sense fields of +7dB (μV/m) at 1 MHz with a 1 kHz bandwidth (ETS-Lindgren, 2017).

- Coaxial Cable: SSB-Electronic GmbH model Ecoflex-10 is a flexible 50 ohm coaxial cable with low attenuation and with an operating frequency range up to 6 GHz.

4.3 Positioning and set up of the vehicle

The vehicle set up within Vela9 is shown in Figure 3. The car was fixed on the roller bench and then the cost down procedure was launched in order to achieve the dyno road loads by giving in input the road loads data, provided by the manufacturer within the certificate of conformity (CoC) of the vehicle, to the Dyno MMI software. Values are reported in Table 2.

Figure 3. Test set up of the Hyundai Nexo within Vela 9 laboratory.

Source: JRC, 2021.

Table 2. Road Load and Dyno Road Load for the vehicle Hyundai Nexo.

Road Load			
F0: 178.70 N	F1: 0.9190N/(km/h)	F2: 0.040370 N/(km/h)^2	Test mass: 2030 kg
Dyno Road Load			
F0: -11.644 N	F1: 0.45840 N/(km/h)	F2: 0.040365 N/(km/h)^2	

Source: JRC, 2021.

The different antennas, used according with the frequency range, were kept at a fixed distance of 10 meters from the closest point for all the sides (left, right, front and rear) of the vehicle under test compared to the tip of the antenna.

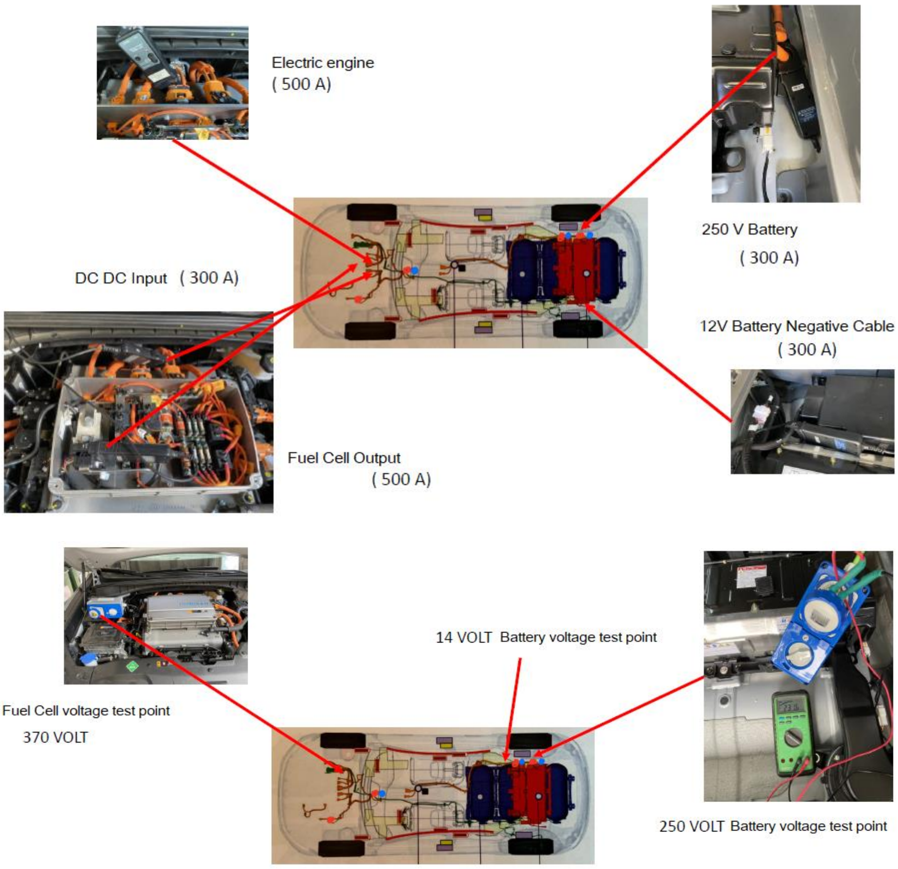
Part of the test campaign was conducted with the vehicle equipped with electrical measuring equipment. In fact, the vehicle was subject to invasive interventions in order to place probes for currents and voltages measurements (Figure 4). Acquired data were needed to perform a deeper analysis at a later stage regarding on road testing.

Figure 4. High voltage safety box and other invasive interventions.

Source: JRC, 2021.

Figure 5 represents a scheme of the interventions made to the vehicle, indicating where the current probes are placed and the voltage test points. Current sample points were placed in correspondence of the electric motor, the high voltage battery, the DC DC input, the fuel cell output and of the 12V battery. Voltages of the batteries (12V and 250V) and voltage at the fuel cell test point were measured. The high voltage from the battery was measured by means of a power analyser. Staff's safety was ensured by means of a box made by a relay and fuses placed between the instrument and the high voltage battery.

Figure 5. Voltage and current clamps sample points.



Source: JRC, 2021.

4.4 Test protocol

With the aim to have a common comparable scenario for the different vehicles, the protocol of test was substantially the same used for previous test campaigns and explained in (Pliakostathis et al., 2020; Pliakostathis et al., 2018; Pliakostathis, 2019; Pliakostathis et al., 2019).

Radiated emissions were measured within the frequency range 30 – 1000 MHz at a constant speed of 40km/h, for the left and right side of the vehicle, as foreseen by Regulation n.10. In addition, also other constant speeds as 60, 80, 100 and 120 km/h as well as the front and rear side of the vehicle were assessed going beyond Regulation n.10 requirements. These measurements were performed with the ECO driving mode activated and the log-periodic antenna vertically polarized (V - pol). Two more measurements in Normal mode at 40 km/h and 120 km/h and two measurements at 40 km/h and 100 km/h in ECO mode, with the antenna horizontally polarized, were added for each position. Three measurements at 40, 80, 120 km/h were carried out in ECO mode by means of the 360 degrees rotation of the turntable with the aim to investigate the presence of EMIs at critical frequencies not identified with the measurements at fixed positions.

Within the frequency range 1 – 6 GHz two measurements at 40 km/h and 100 km/h were performed in ECO mode for each antenna polarization with a dwell time of 5ms for the peak detector as recommended by CISPR12 for the frequency band from 30 to 1000 MHz.

Once identified the worst driving mode conditions in terms of radiated emissions, the spectrogram analysis was conducted within the frequency range 30 – 54 MHz for each position in Normal mode with three customized driving cycles (0-40km/h-0, 0-120 km/h, “stepped”, a mix of accelerations/constant speeds/decelerations, from 40km/h to 120 km/h). In this case, the maximum frequency band scan allowed by the signal receiver is 24 MHz and the selected dwell time is 500ms. Within this frequency range a spectrogram was also acquired with the vehicle placed with its left side in front of the antenna. For that test setup, the stepped driving cycle and the 3rd recuperation level of the ECO + regenerative braking were assessed. Time domain analysis for single critical frequency was carried out with the vehicle driven in Normal mode and the stepped driving cycle. The case of no road load applied to the dynamometer was also explored. It was considered the left side of the vehicle and the driving mode that generates more and higher EMIs and two different constant speeds (40 km/h and 100 km/h).

In addition, 360 degrees rotations were performed at different constant speeds (40, 60, 80, 100, 120 km/h) in Normal Mode within the frequency range 150 kHz – 30MHz.

Only one driver was employed during the test campaign in order to reduce the driver effect on the measurements.

Measurements were performed selecting the continuous sweep option of the EMI receiver, with a sweeping period of 20 seconds at least and the max hold value activated for the peak trace.

The test protocol was repeated twice in order to take into account the radiated disturbances generated by the vehicle after the invasive interventions done to acquire the vehicle’s electrical parameters.

5 Results of the test campaign

5.1 30 MHz – 1000 MHz

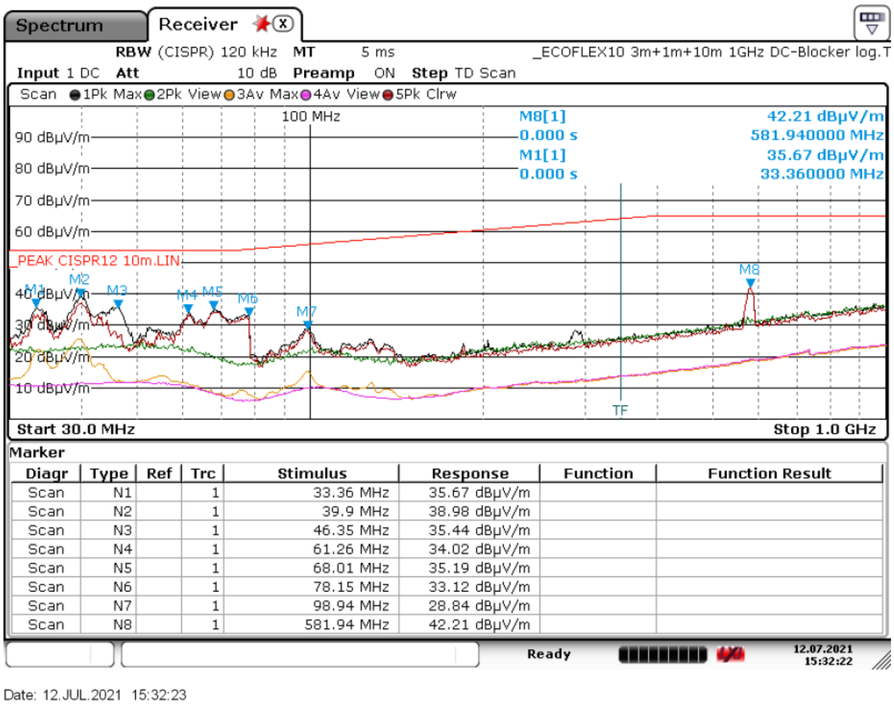
Different sides of the vehicle (left, right, rear and front) were tested in the frequency domain (30 MHz – 1000 MHz). For each side, the vehicle was driven at constant speeds (40, 60, 80, 100, 120 km/h) with the ECO mode activated and the log-periodic antenna vertically polarized (V - pol). In addition, two measurements in Normal mode at 40 km/h and 120 km/h and two measurements in ECO mode at 40 km/h and 100 km/h, with the antenna horizontally polarized were performed for each position, being this case less critical. The 360 degrees rotation of the turntable was performed at three different speeds (40, 80, 120 km/h) in ECO mode in order to identify the presence of any other critical frequencies not observed at fixed positions.

5.1.1 Positioning of the vehicle

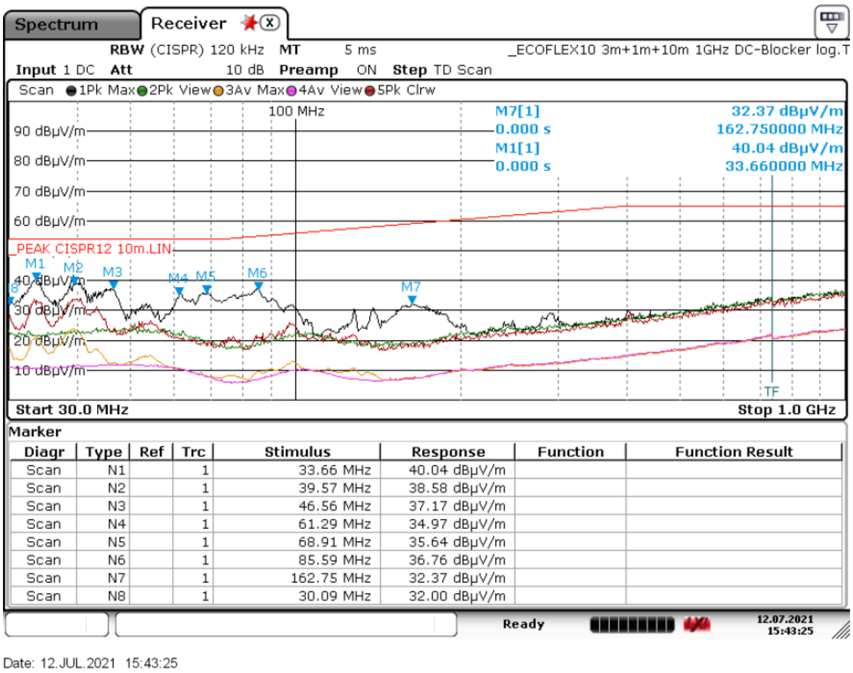
Figure 6, Figure 7, Figure 8 and Figure 9 report the measurements performed in ECO mode at two constant speeds of 40 km/h and 120 km/h for each side of the vehicle (left, right, rear and front) with the antenna vertically polarized.

The left side of the vehicle is the case where more disturbances were observed over the entire frequency range 30 MHz – 1 GHz. The highest peak of 40.04 dBµV/m was recorded at 33.66MHz in the case of a constant speed of 120km/h (Figure 6 - b). The front side of the vehicle resulted slightly worse than the rear side, with the highest recorded peak of 45.37 dBµV/m at 41.04MHz for a constant speed of 120km/h (Figure 9). An interesting finding concerns the tests conducted with the vehicle positioned in front of the antenna in Figure 9. Indeed, despite for most of the frequencies the level of EMIs follows the increase the speed, for the one around 52 MHz, a decrease of disturbances was observed. In fact, a value 41.46dBµV/m was recorded during the test at 40 km/h, while a value of 36.79dBµV/m was recorded during the test at 120 km/h.

Figure 6. Vehicle positioned with its left side versus the antenna (V-pol), driven at a constant speed of 40 km/h (a) and of 120 km/h (b) in ECO mode.



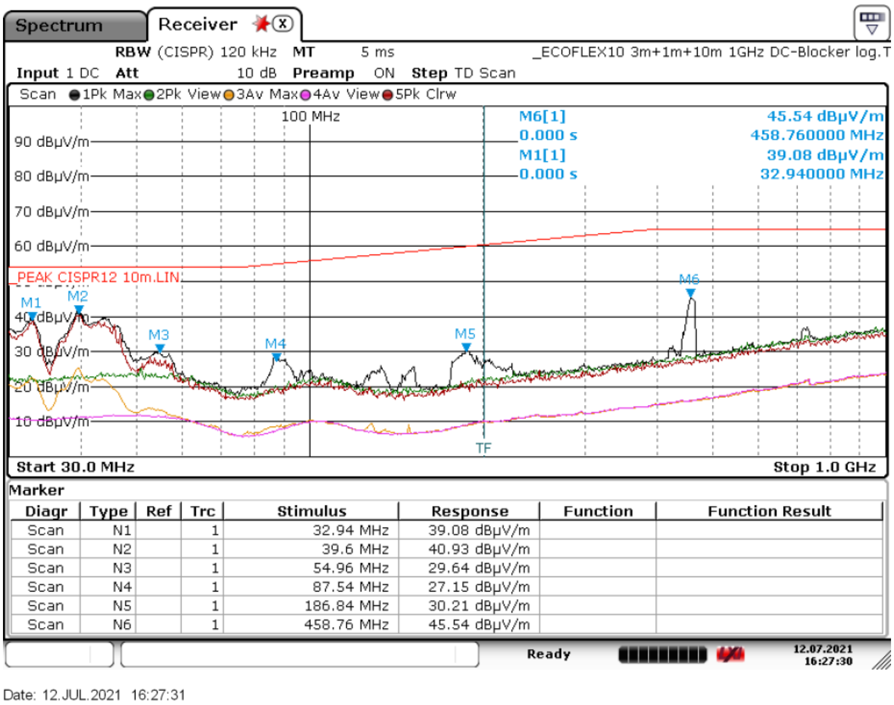
(a)



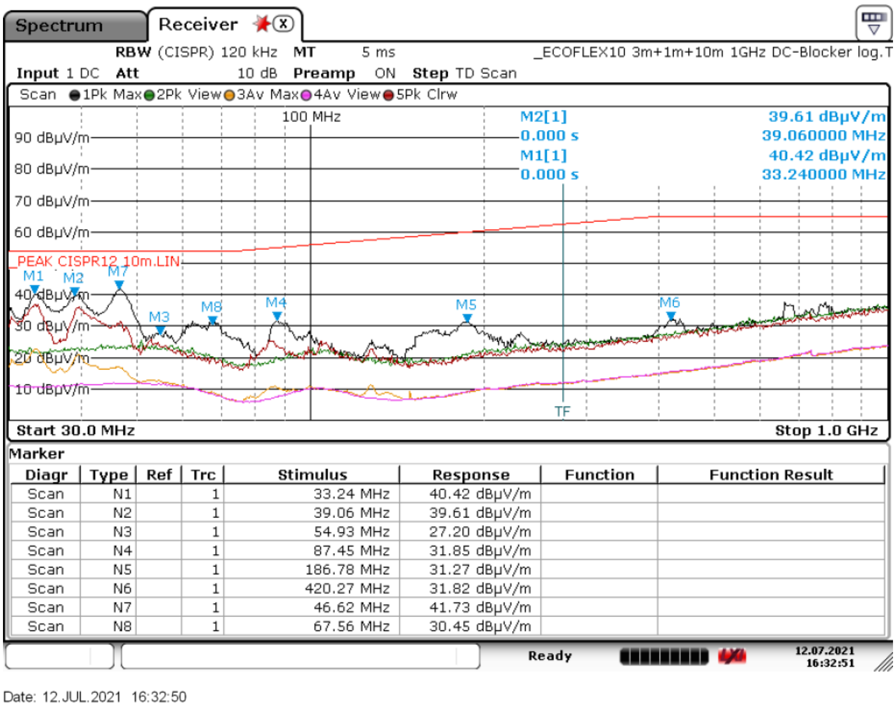
(b)

Source: JRC, 2021.

Figure 7. Vehicle positioned with its right side versus the antenna (V-pol), driven at a constant speed of 40 km/h (a) and of 120 km/h (b) in ECO mode.



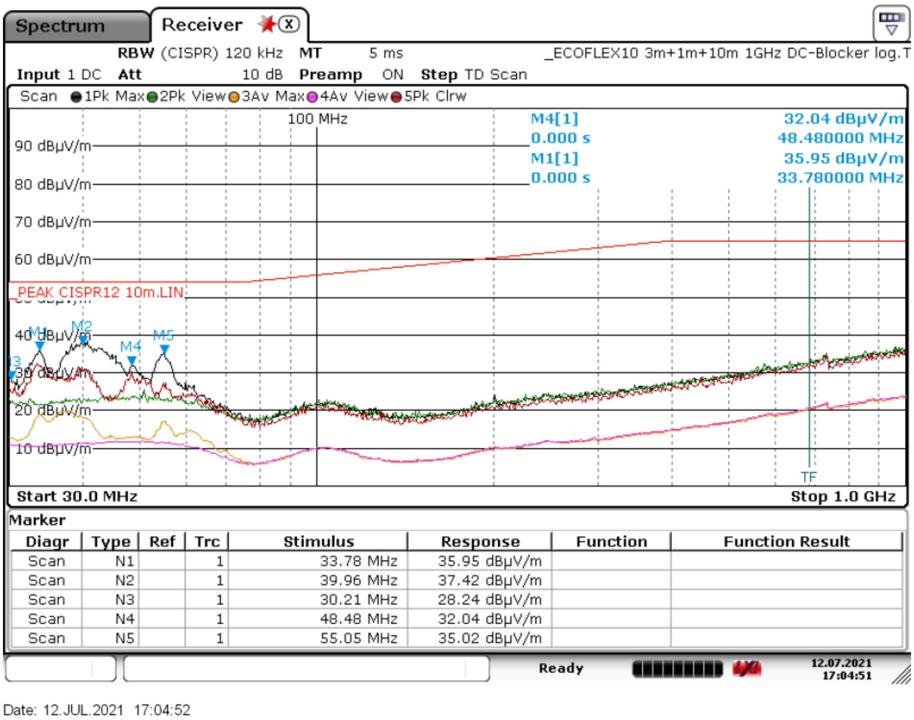
(a)



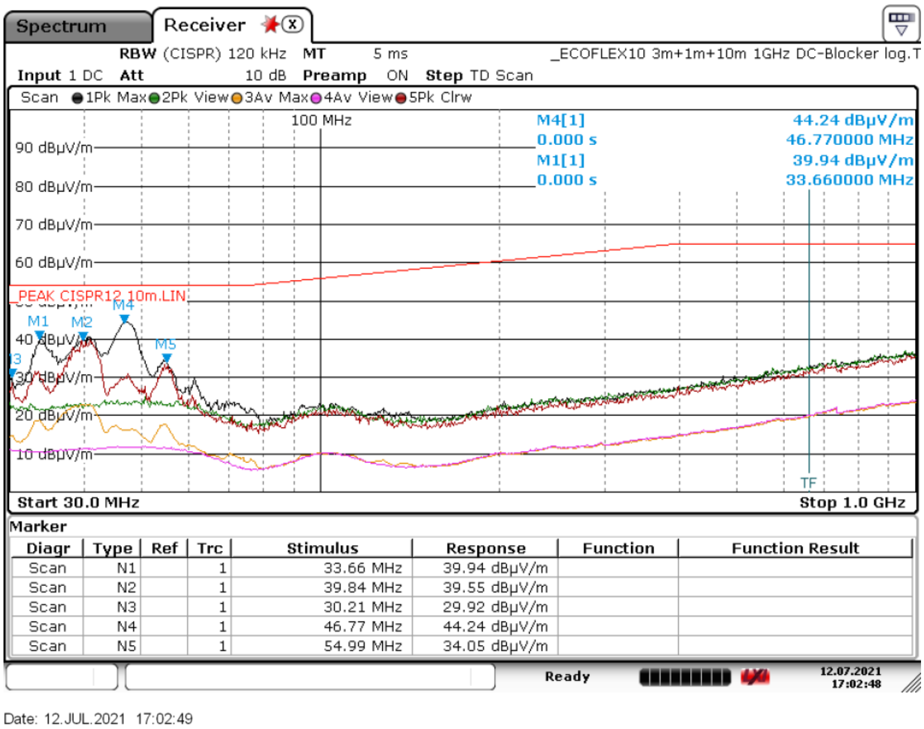
(b)

Source: JRC, 2021.

Figure 8. Vehicle positioned with its rear versus the antenna (V-pol), driven at a constant speed of 40 km/h (a) and of 120 km/h (b) in ECO mode.



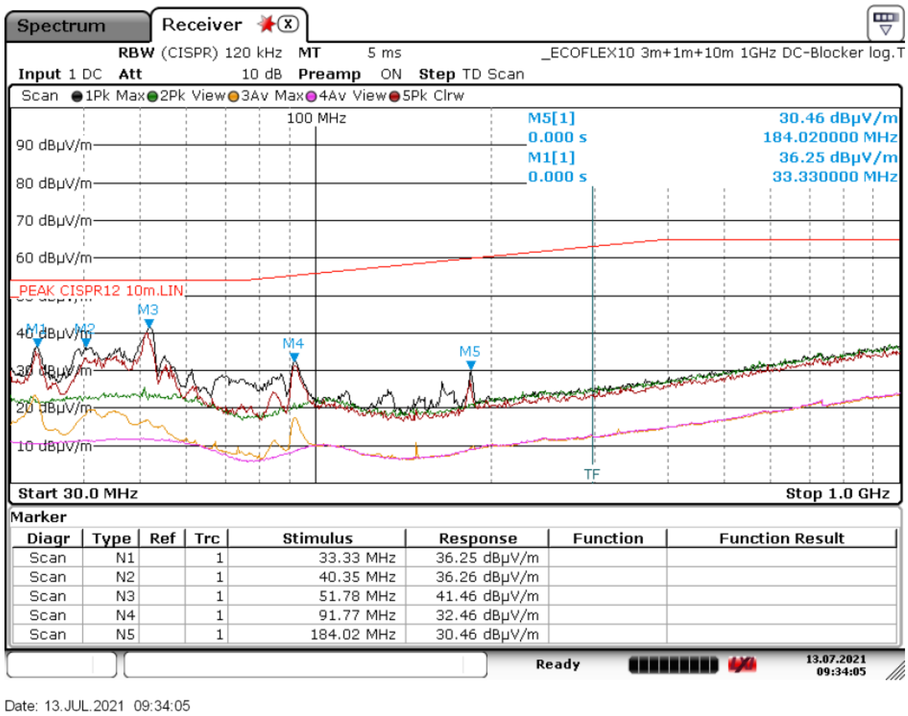
(a)



(b)

Source: JRC, 2021.

Figure 9. Vehicle positioned with its front versus the antenna (V-pol), driven at a constant speed of 40 km/h (left) and of 120 km/h (right) in ECO mode.



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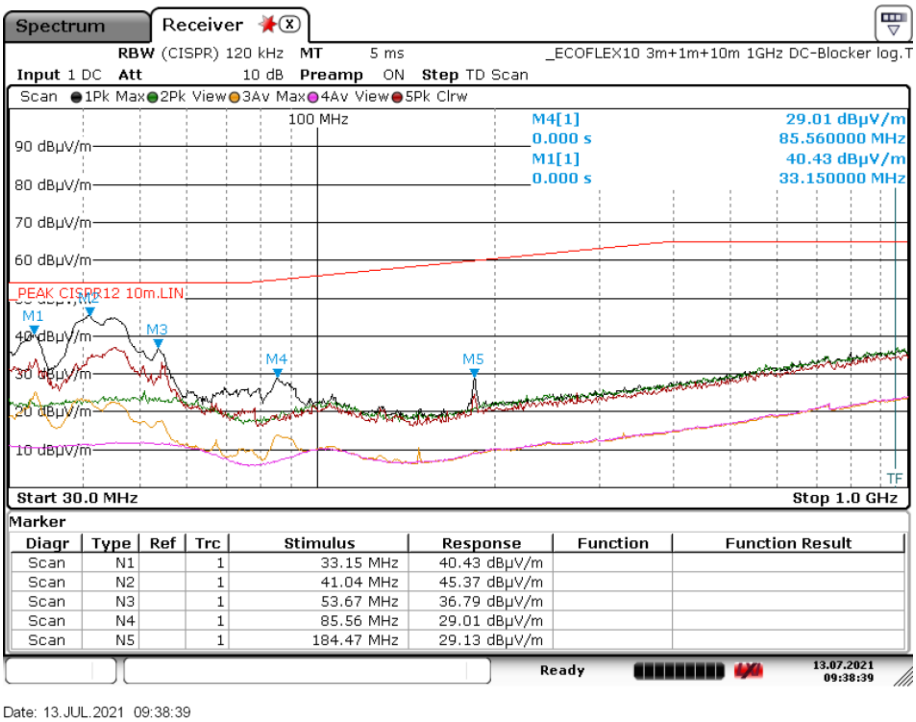


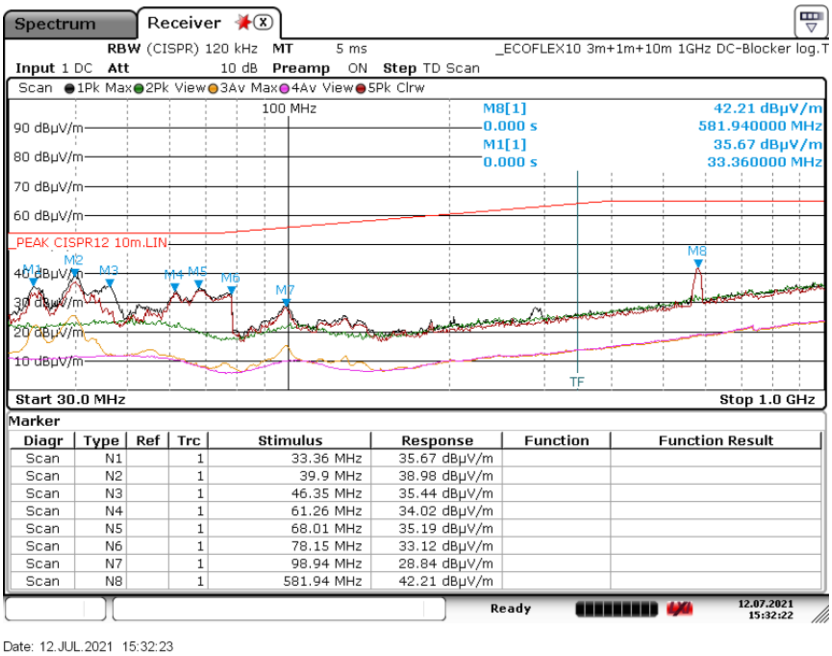
(b)

Source: JRC, 2021.

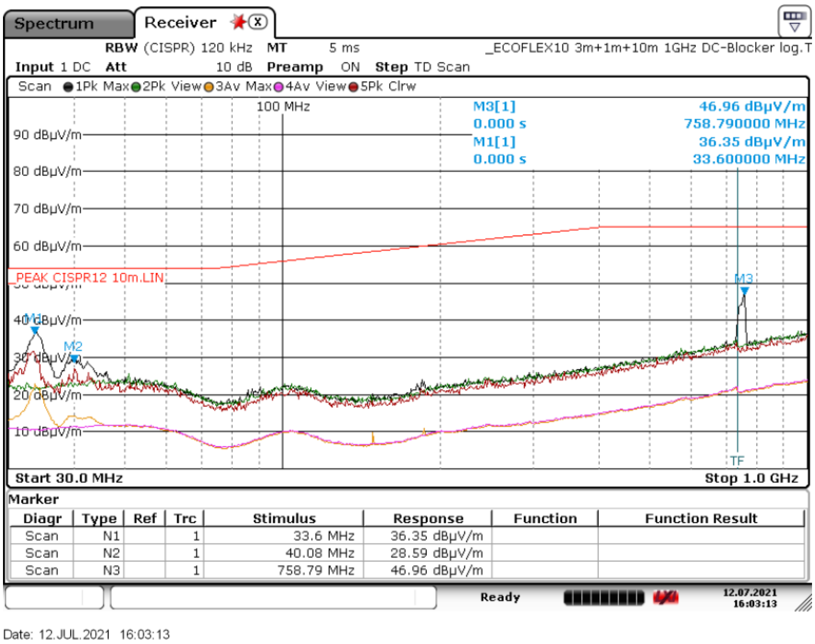
5.1.2 Vertical vs Horizontal Antenna Polarization

Figure 10 and Figure 11 show the results of the measurements performed with vehicle driven at the constant speeds of 40 km/h and 100 km/h, in ECO mode, and placed with its left side versus the vertically polarized antenna. It appears clear and evident that the vertical polarization (Figure a) is the most critical condition in terms of radiated emissions. This was observed for each tested side of the vehicle.

Figure 10. Vehicle driven at a constant speed of 40 km/h, in ECO mode, positioned with its left side versus the antenna vertically polarized (a) and horizontally polarized (b).



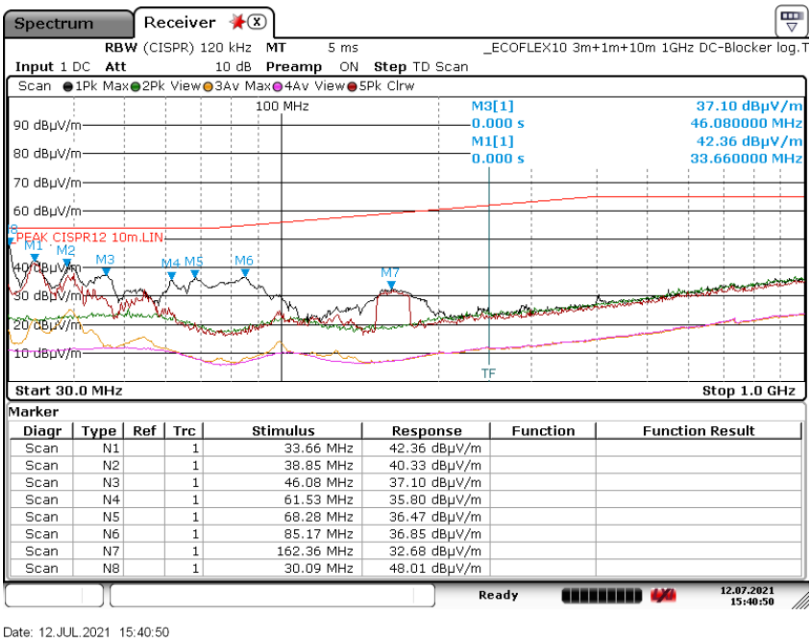
(a)



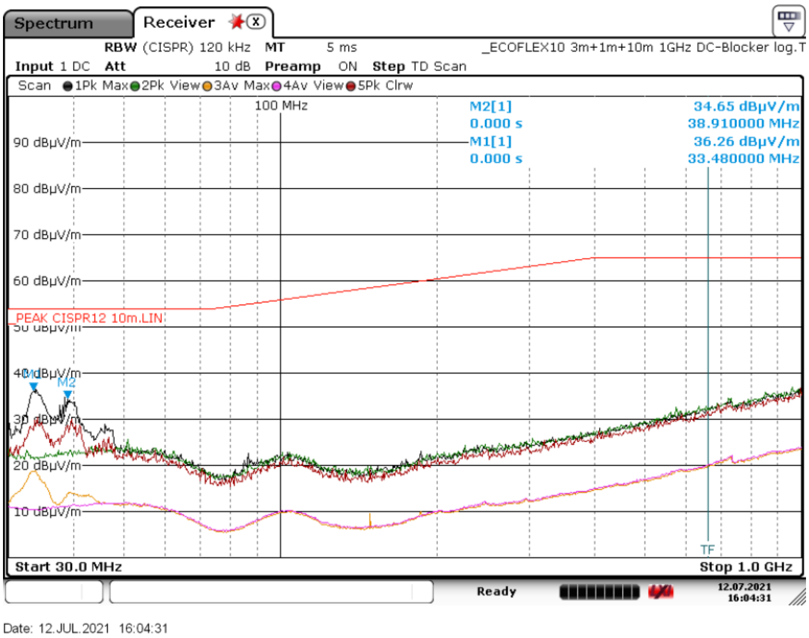
(b)

Source: JRC, 2021.

Figure 11. Vehicle driven at a constant speed of 100 km/h, in ECO mode, positioned with its left side versus the antenna vertically polarized (a) and horizontally polarized (b).



(a)



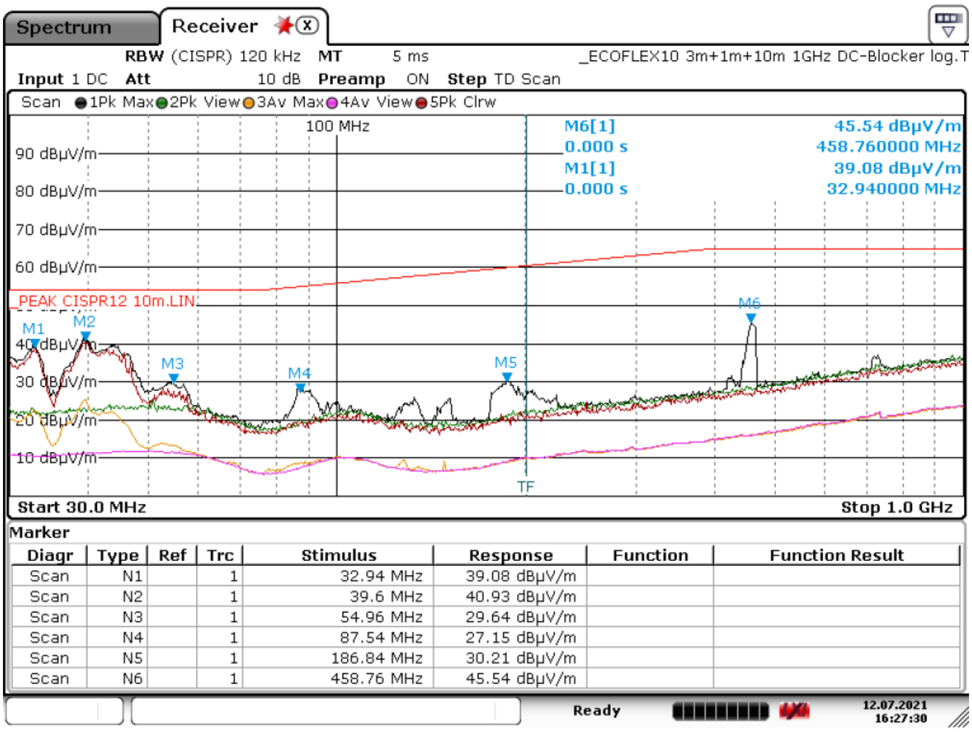
(b)

Source: JRC, 2021.

5.1.3 Vehicle driving modes

The effect of two different driving modes (Normal and ECO) on radiated emissions was investigated for each tested side of the vehicle. Figure 11 and Figure 12 report measurements performed at two different constant speeds of 40 km/h and 120 km/h, with the antenna vertically polarized.

Figure 12. Vehicle positioned with its left side versus the antenna (V-pol), driven at a constant speed of 40 km/h, in ECO driving mode (a) and in Normal mode (b)



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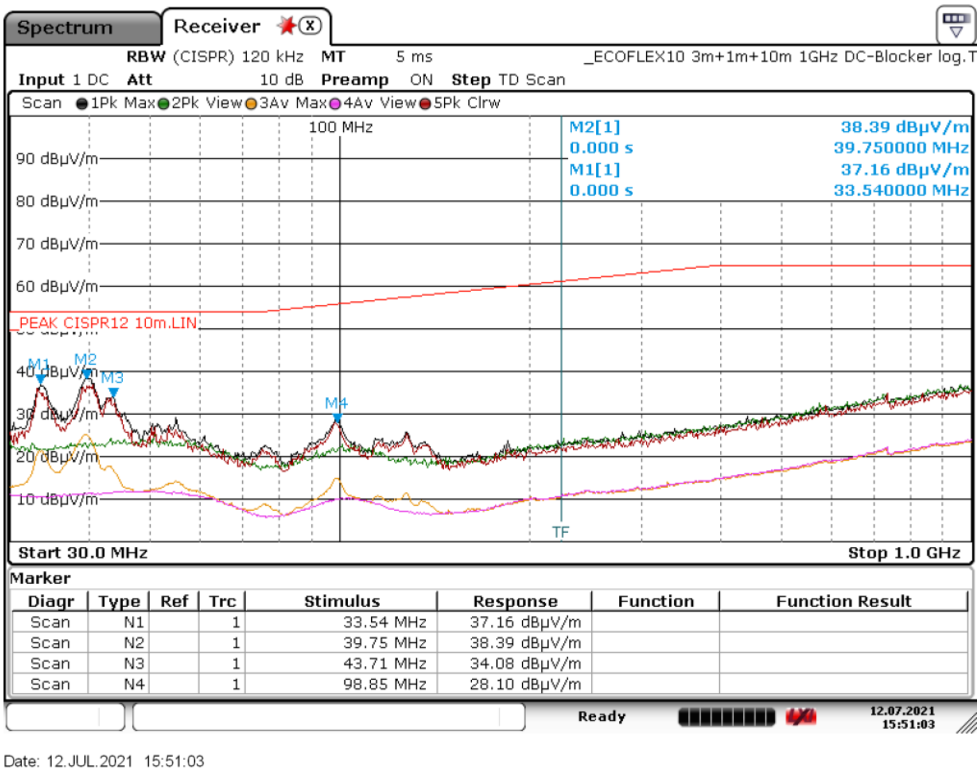
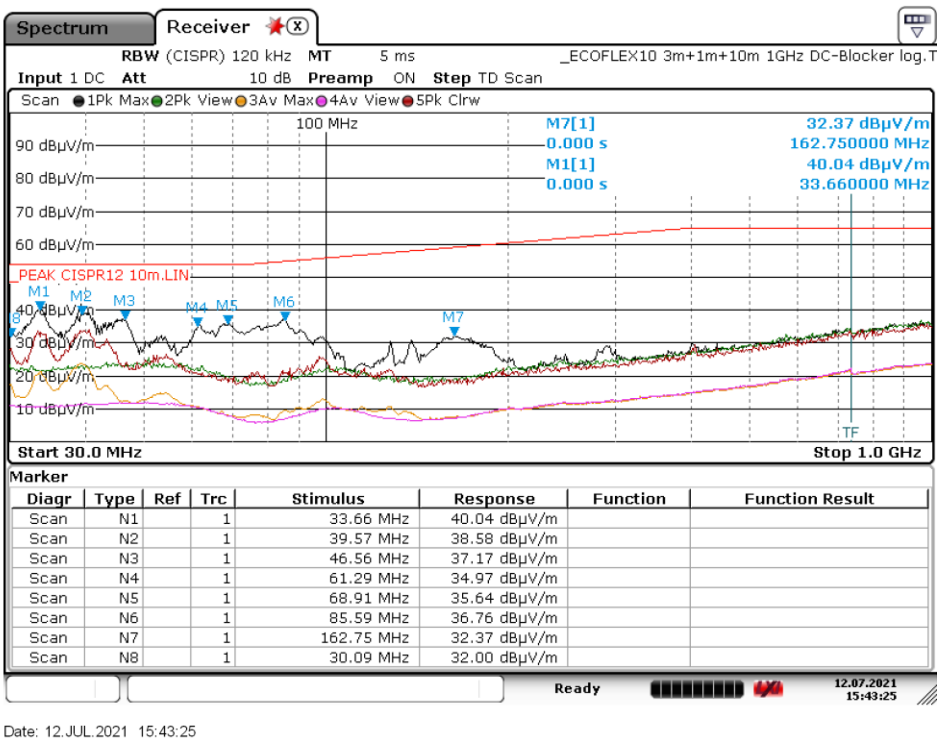
(a)



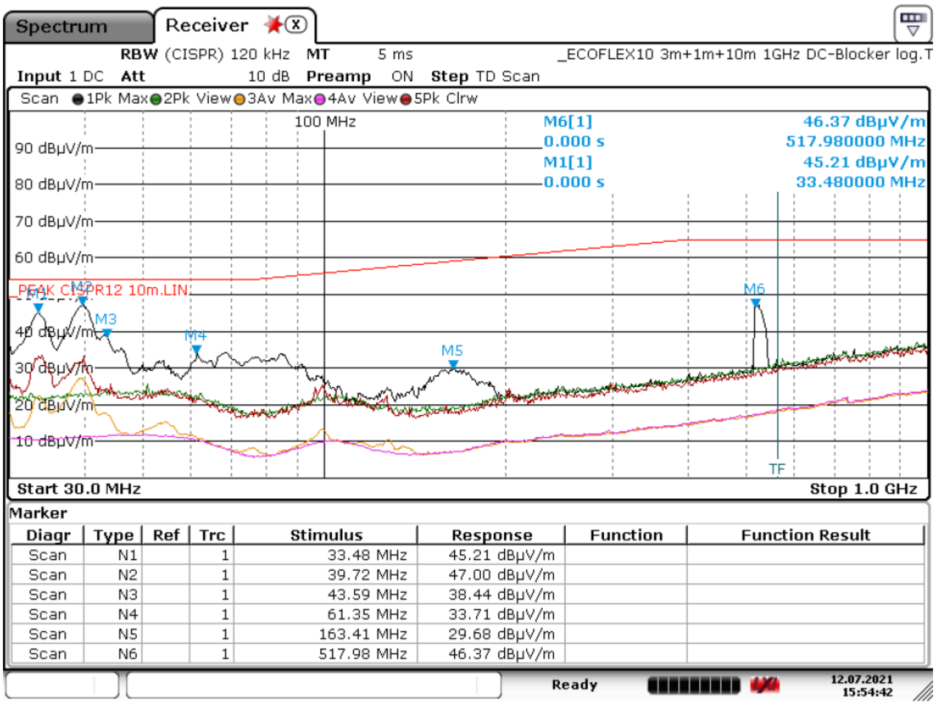
(b)

Source: JRC, 2021.

Figure 13. Vehicle positioned with its left side versus the antenna (V-pol), driven at a constant speed of 120 km/h, in ECO driving mode (a) and in Normal mode (b)



(a)



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(b)

Source: JRC, 2021.

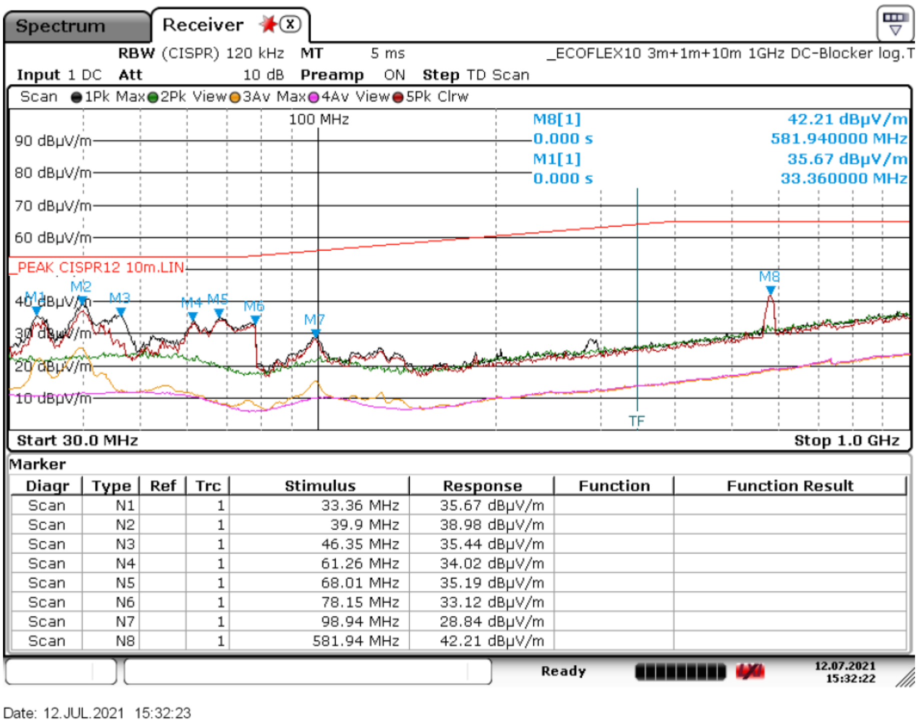
Figure 13 refers to the vehicle driven at 120 km/h. The vehicle driven in normal mode produced higher EMIs at different frequencies compared to the ECO mode, as indicated by the markers. Highest peaks at lower frequencies reached values of 45.21 dBµV/m at 33.48 MHz and of 47 dBµV/m at 39.72 MHz; a value of 38.44 dBµV/m was recorded at 43.59 MHz, 46.37 dBµV/m at 517.98 MHz (Figure b).

This result confirms the energy saving nature of the ECO mode, which results in less emitted EMIs compared to the Normal mode. This result is also confirmed for each tested vehicle side. However, only the case of the left side of the vehicle is graphically reported.

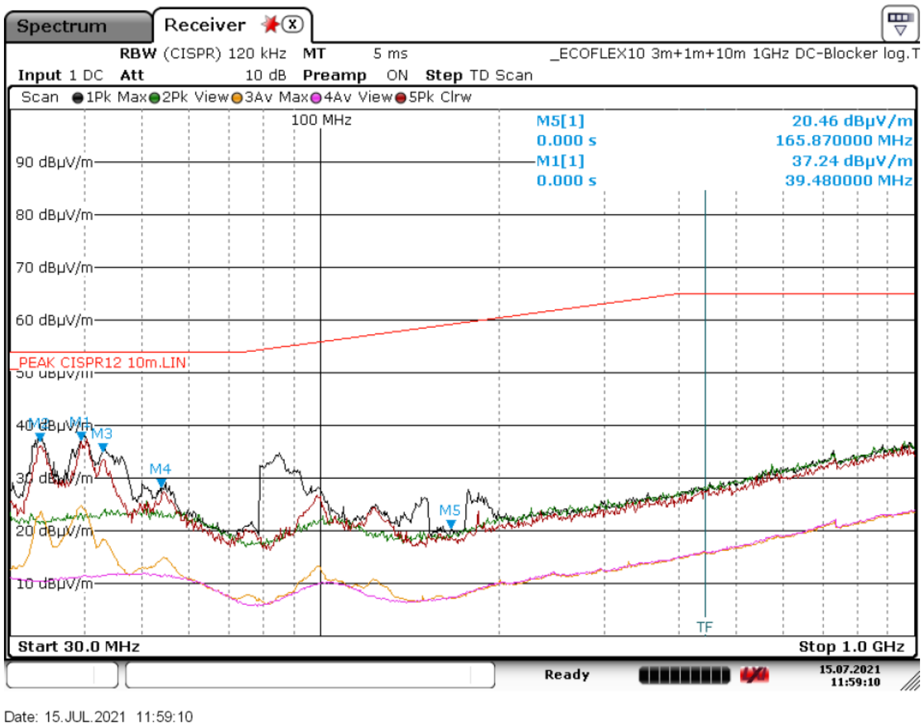
5.1.4 No Road load

Figure 14 and Figure 15 show the tests executed with the vehicle placed with its left side versus the antenna, which was vertically polarized, and the selected driving mode was the Normal mode. The tests were conducted at constant speeds of 40 km/h and 120 km/h with and without road loads within the dyno roller bench software. As can be seen from pictures, this condition does not significantly influence the results for the main band of frequencies under investigation (i.e. from 30 to 61 MHz).

Figure 14. RE, vehicle placed with its left side versus the antenna (V-pol), at a constant speed of 40 km/h with dyno road load (a) and without road load (b), Normal mode.



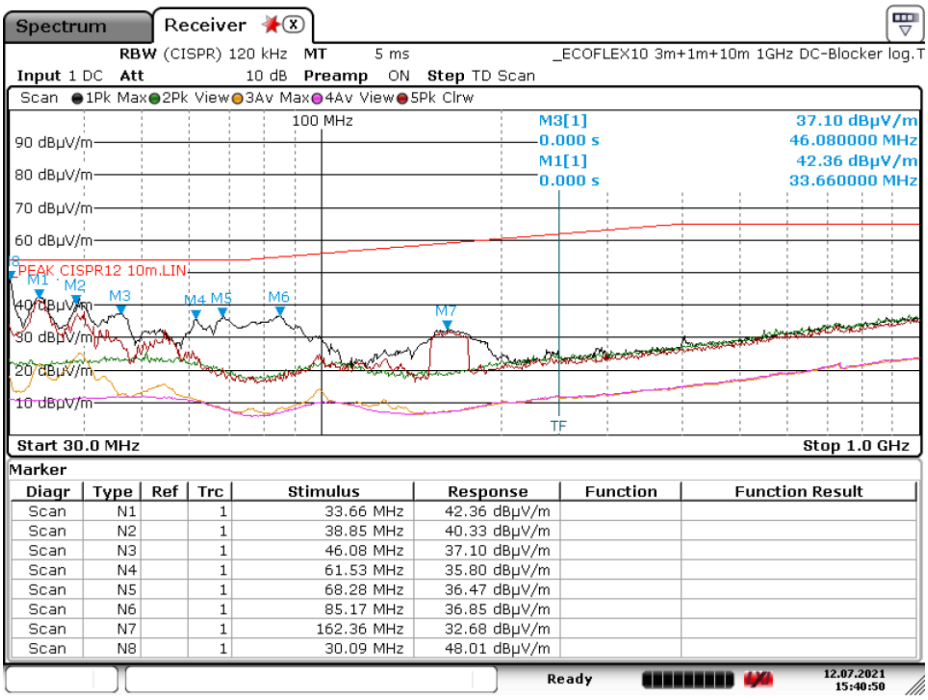
(a)



(b)

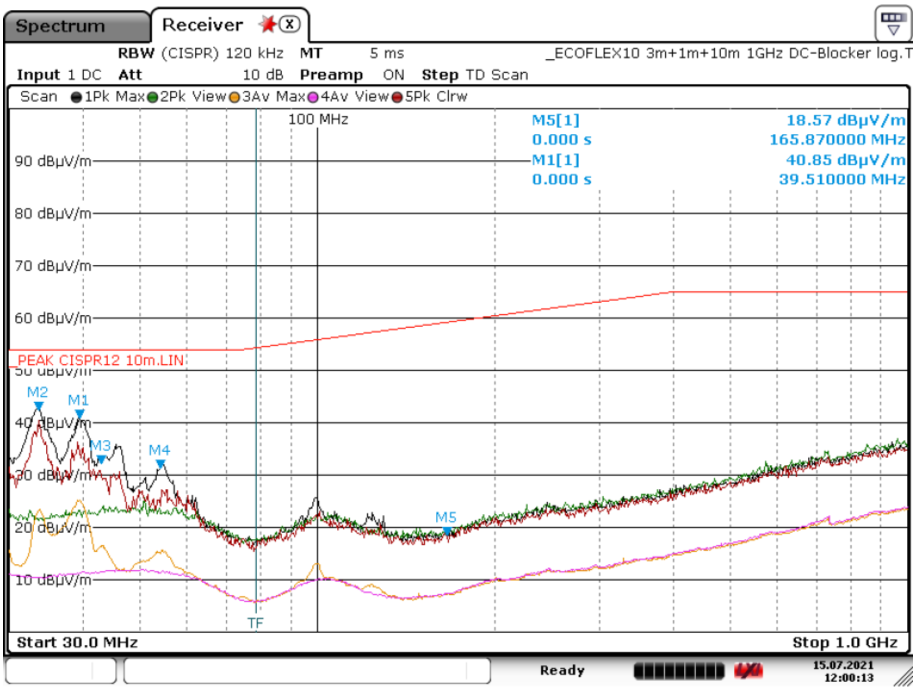
Source: JRC, 2021.

Figure 15. RE, vehicle placed with its left side versus the antenna (V-pol), at a constant speed of 100 km/h with dyno road load (a) and without road load (b).



Date: 12.JUL.2021 15:40:50

(a)



Date: 15.JUL.2021 12:00:13

(b)

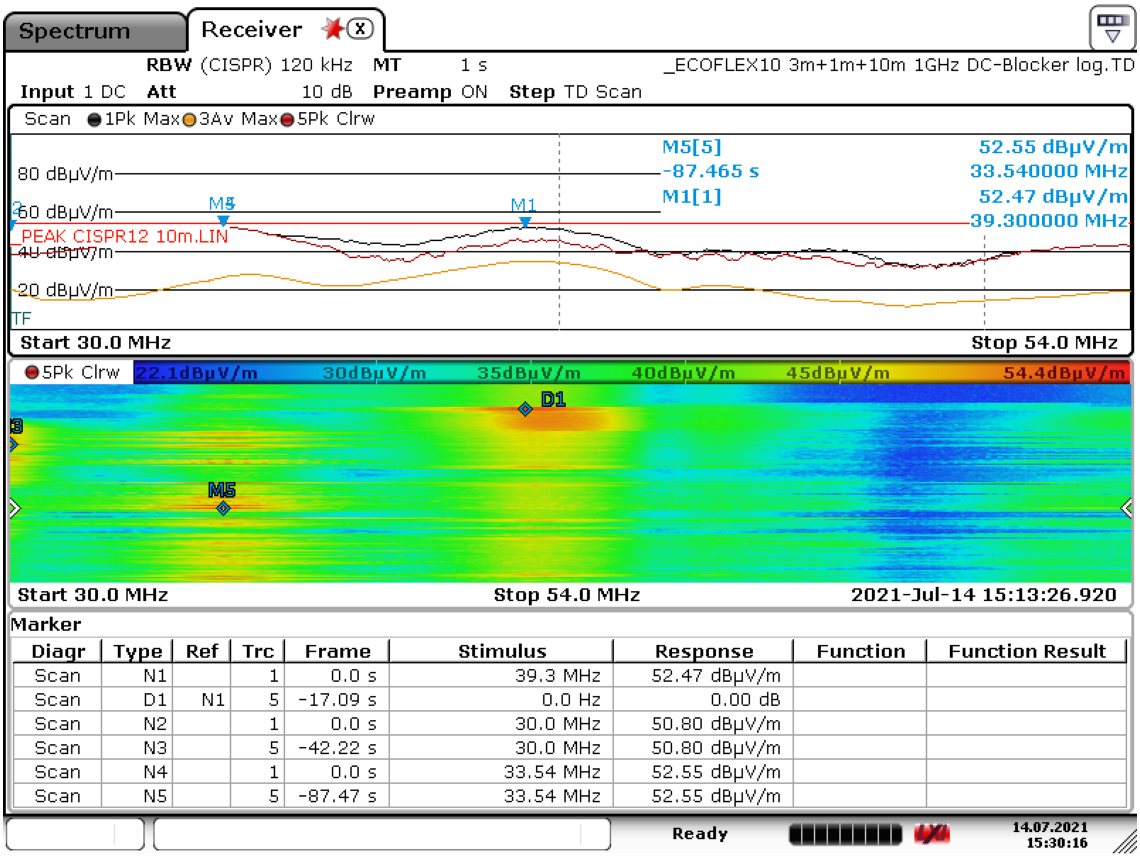
Source: JRC, 2021.

5.1.5 Spectrogram analysis

The spectrogram consists of a time-frequency representation of the spectrum, being the time represented in the vertical axis, oriented from top to the bottom, with more recent data placed on the top of the graph. Frequencies are indicated on the horizontal axis and the amplitude of the detected EMI is represented by different colors, being cold colors corresponding to lower power levels and warm colors to higher power levels. This technique allows for identifying critical frequencies over the time.

Figure 16 shows the spectrogram of the frequency range 30 – 54 MHz referred to the vehicle placed with its left side versus the antenna and driven in Normal mode following customized driving cycle of stepped speeds (0-40-60-80-100-120 km/h).

Figure 16. Spectrogram referred to the frequency range 30 – 54 MHz. The vehicle is placed with its left side versus the antenna (V-pol), driven in Normal mode following customized driving cycle of stepped speeds (0-40-60-80-100-120 km/h).



Date: 14.JUL.2021 15:30:15

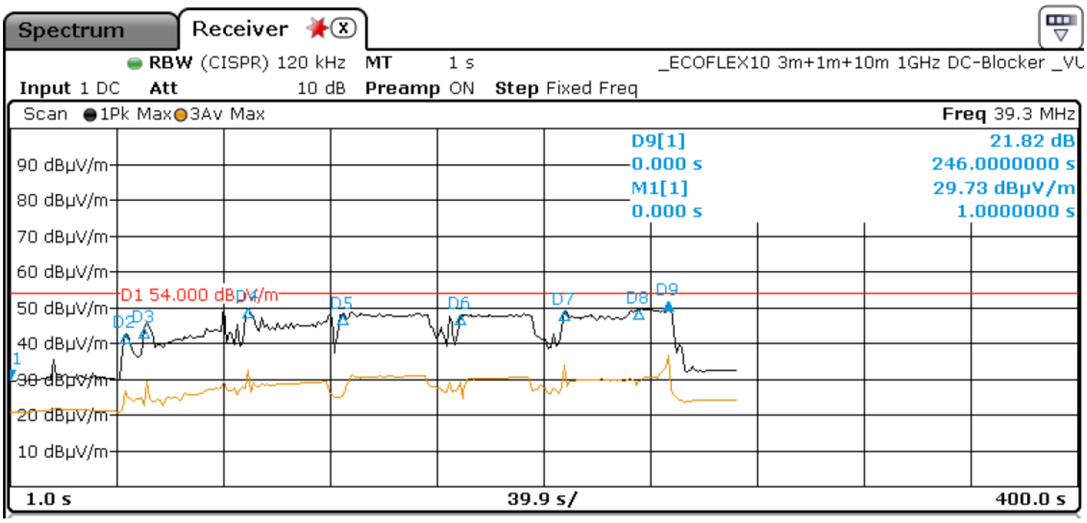
Source: JRC, 2021.

The marker D1 (within the spectrogram) at 39.3MHz corresponds to the peak of 52.47dBµV/m that was registered at the end of the driving cycle when the vehicle reached 0km/h. A peak of 50.8dBµV/m was also recorded at the frequency of 30 MHZ when the vehicle was driven a constant speed of 120 km/h. In addition, a value of 52.55 dBµV/m was observed at 33.54 MHz during the acceleration from 100 km/h and 120 km/h.

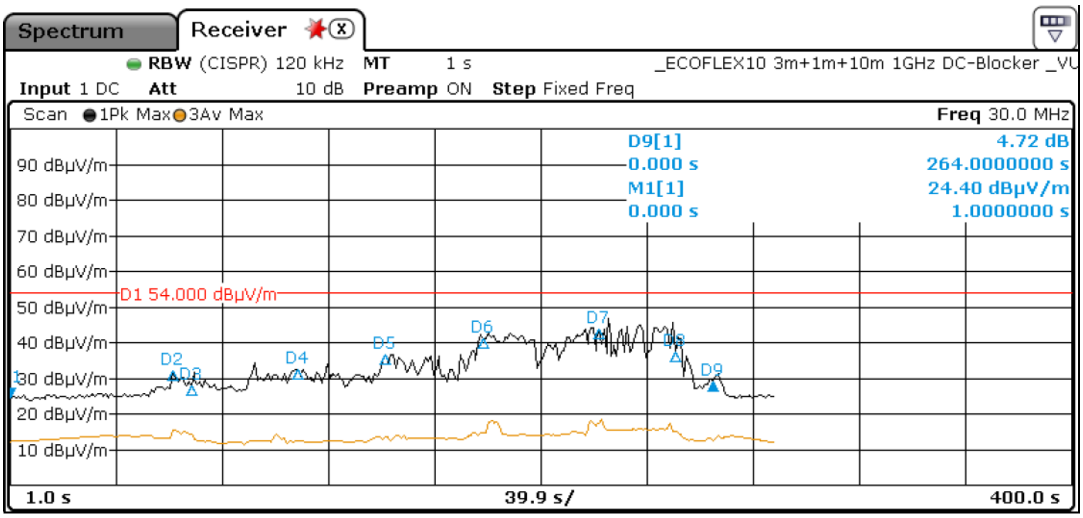
These critical frequencies were investigated by means of a dedicated time domain analysis.

Figure 17 shows the time domain measurements at 39.3 MHz (a) and at 30 MHz (b), executed in Normal mode during a customized driving cycle with stepped speeds (0-40-60-80-100-120 km/h) and V-pol antenna placed on the left of the vehicle.

Figure 17. Time domain measurements at 39.3 MHz (a) and at 30 MHz (b), Normal mode, executed during a customized driving cycle with stepped speeds (0-40-60-80-100-120 km/h) and V-pol antenna placed on the left of the vehicle.



(a)



(b)

Source: JRC, 2021.

Table 3 and Table 4 report the markers description and their absolute values as well as their relative values with respect to the value of E – field (dBµV/m) when the vehicle is in idle mode (P position of the gearbox), for the critical frequencies 39.3 MHz and 30 MHz respectively.

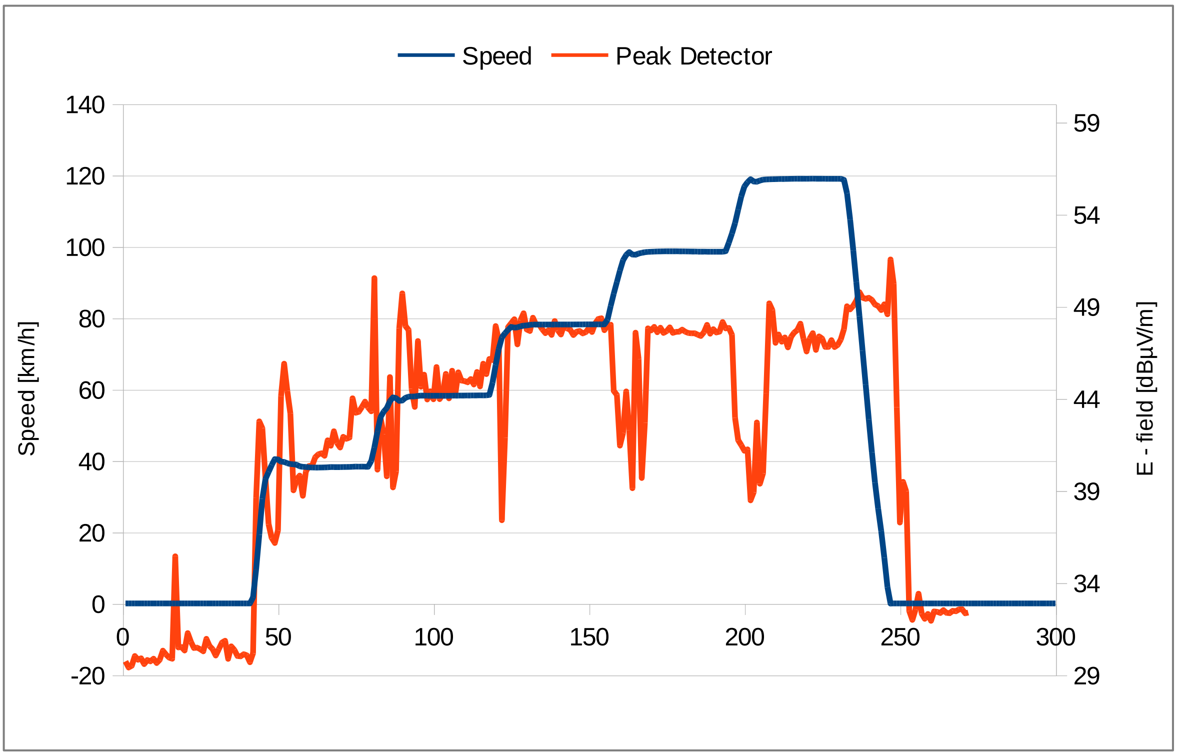
Table 3. Markers caption related to the different phases of the customized driving cycle (critical frequency = 39.3 MHz)

Marker id	Marker description	Marker relative value (dBμV/m)	Marker absolute value (dBμV/m)
M1	Vehicle gear in (P) position	0	29.73
D2	Starting of acceleration	+13.03	42.76
D3	40 km/h constant speed	+14.40	44.13
D4	60 km/h constant speed	+19.98	49.71
D5	80 km/h constant speed	+18.36	48.09
D6	100 km/h constant speed	+18.02	47.75
D7	120 km/h constant speed	+19.43	49.16
D8	Starting of deceleration	+19.58	49.31
D9	0 km/h	+21.82	51.55
D10	Vehicle gear in (P) position		

Source: JRC, 2021.

This test reported in Figure 18 confirms that for the frequency at 39.3 MHz the higher EMI was mainly recorded when the vehicle reached 0 km/h and highlights that during accelerations a significant reduction of EMI was observed. This might be due to the contribution of the battery, which was operating during the accelerations, and helped to reduce the EMIs especially for the accelerations at higher speeds like from 80 to 100 km/h and from 100 to 120 km/h.

Figure 18. Time domain analysis, critical frequency 39.3 MHz, E – field and speed vs time, normal mode, customized stepped driving cycle, V-pol antenna placed on the left of the vehicle.



Source: JRC, 2021.

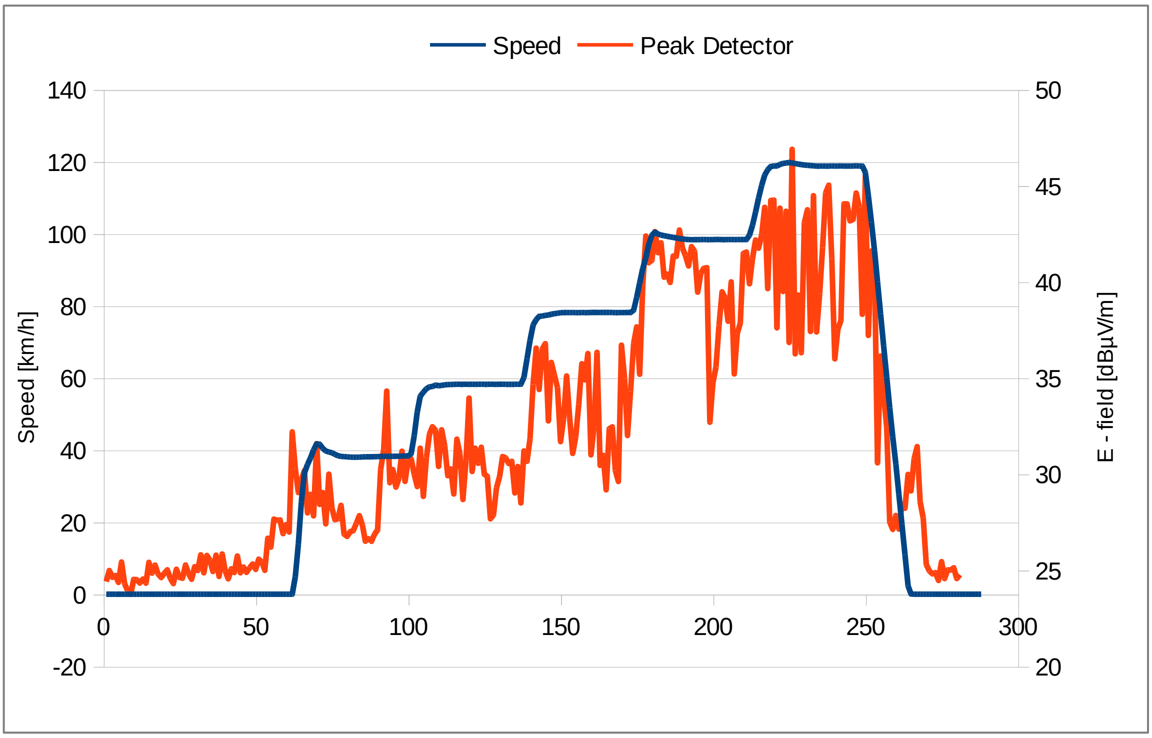
Table 4. Markers caption related to the different phases of the customized driving cycle (critical frequency = 30 MHz)

Marker id	**Marker description**	**Marker relative value (dBμV/m)**	**Marker absolute value (dBμV/m)**
M1	Vehicle gear in (P) position	0	24.4
D2	Starting of acceleration	+7.78	32.18
D3	40 km/h constant speed	+3.42	27.82
D4	60 km/h constant speed	+7.87	32.27
D5	80 km/h constant speed	+12.72	37.12
D6	100 km/h constant speed	+16.59	40.99
D7	120 km/h constant speed	+19.42	43.82
D8	Starting of deceleration	+12.81	37.21
D9	0 km/h	+4.72	29.12
D10	Vehicle gear in (P) position		

Source: JRC, 2021.

Concerning the critical frequency of 30 MHz, the time domain analysis in Figure 19 confirms that the highest peak was recorded at a constant speed of 120 km/h, highlighting the connection between EMIs amplitude and the increase of the speed.

Figure 19. Time domain analysis, critical frequency 30 MHz, E – field and speed vs time, normal mode, customized stepped driving cycle, V-pol antenna placed on the left of the vehicle.

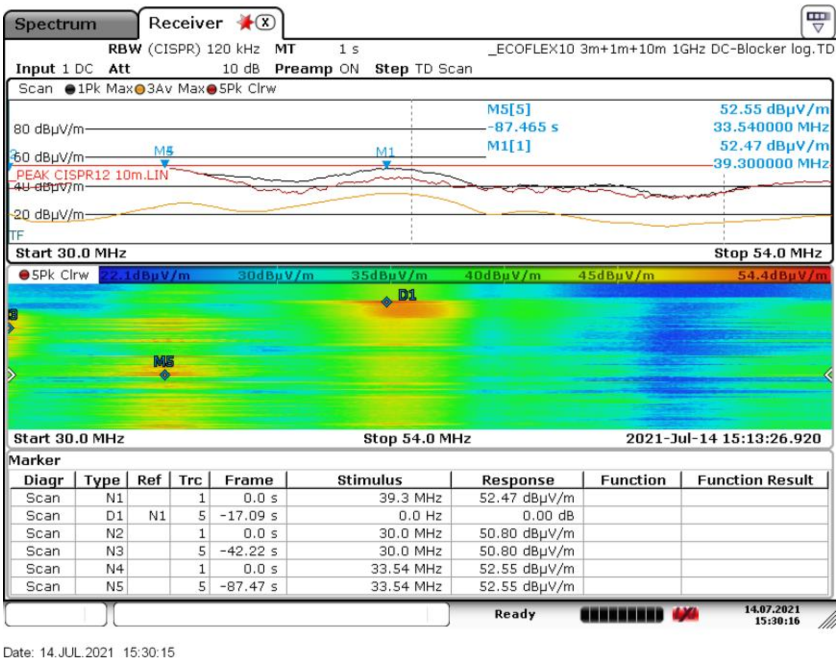


Source: JRC, 2021.

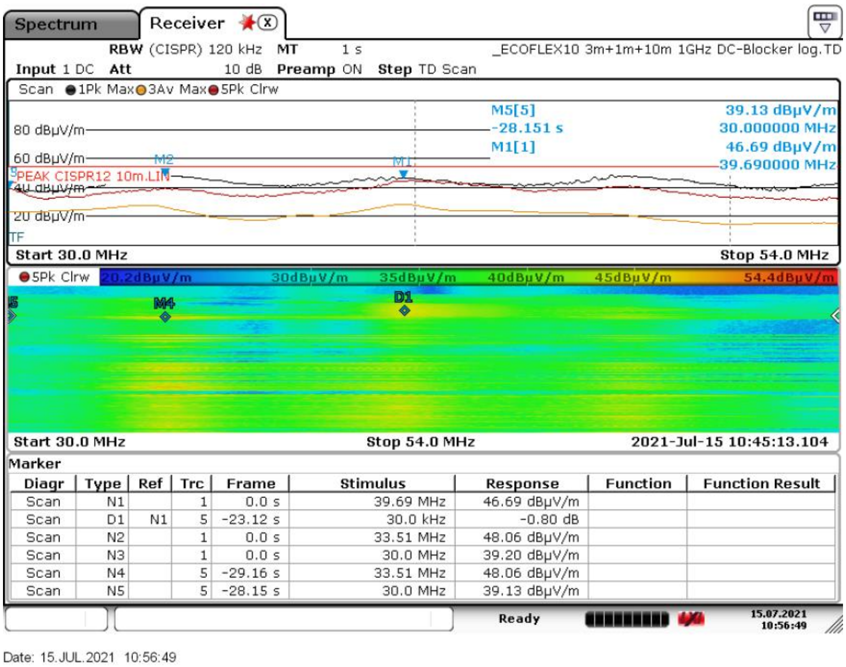
It is worth to underline that speed data were acquired with the software of the roller benches and then processed together with data from the EMI receiver. This resulted in a certain degree of uncertainty in time alignment.

Spectrogram analysis was also used to confirm the results obtained regarding the positioning of the vehicle compared to the antenna. By looking at colours of graphs it is evident that higher levels of disturbances were recorded when the vehicle was placed on its left and front sides compared to the tip of the antenna, as shown in Figure 20 and Figure 21.

Figure 20. Spectrograms referred to the frequency range 30 – 54 MHz, Normal mode, customized driving cycle of stepped speeds (0-40-60-80-100-120 km/h), V-pol antenna placed on the left (a) and on the right (b) of the vehicle.



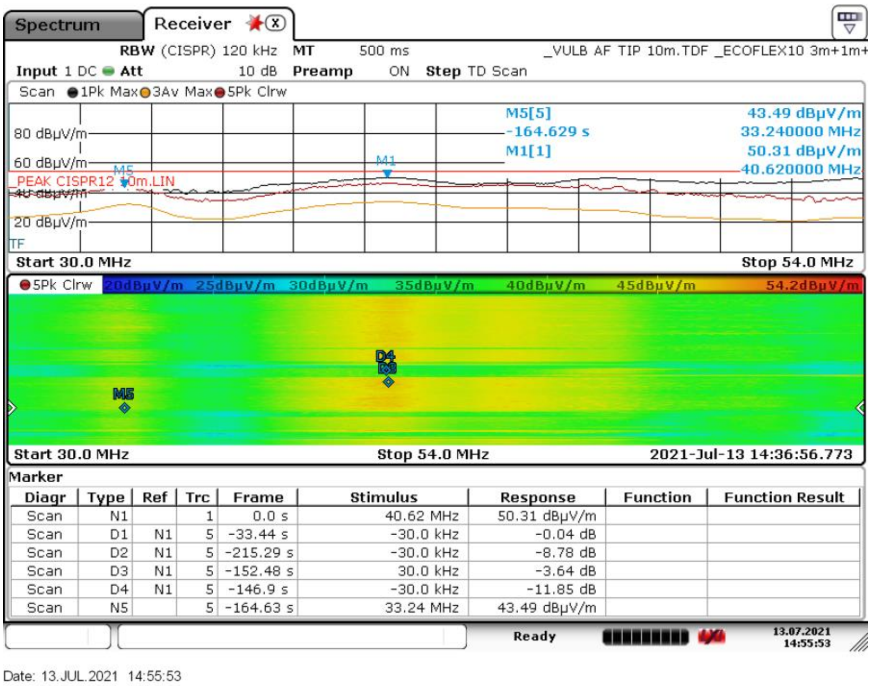
(a)



(b)

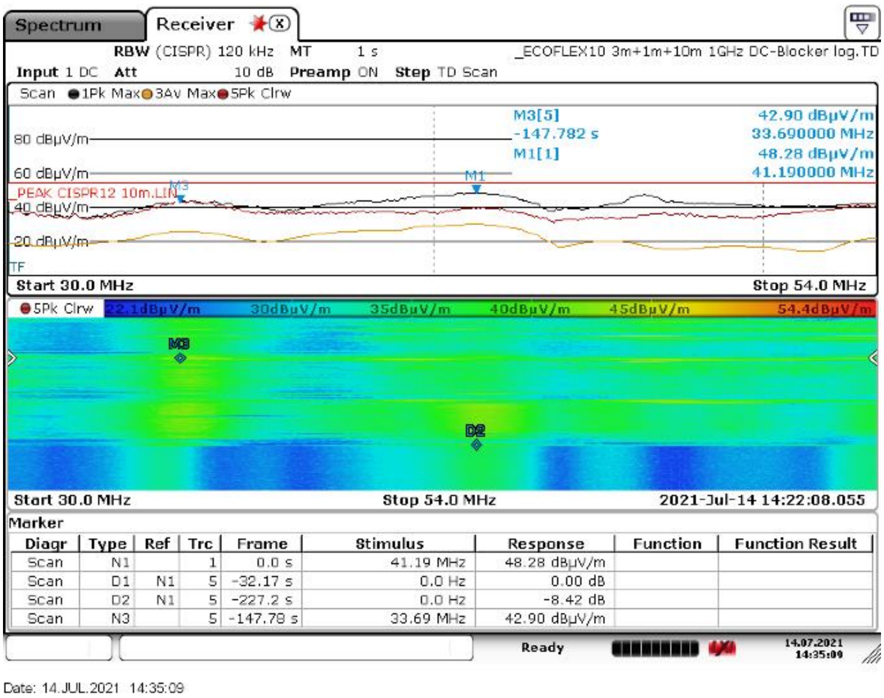
Source: JRC, 2021.

Figure 21. Spectrograms referred to the frequency range 30 – 54 MHz, Normal mode, customized driving cycle of stepped speeds (0-40-60-80-100-120 km/h), V-pol antenna placed in front (a) and at the rear (b) of the vehicle.



Diagr	Type	Ref	Trc	Frame	Stimulus	Response	Function	Function Result
Scan	N1		1	0.0 s	40.62 MHz	50.31 dBµV/m		
Scan	D1	N1	5	-33.44 s	-30.0 kHz	-0.04 dB		
Scan	D2	N1	5	-215.29 s	-30.0 kHz	-8.78 dB		
Scan	D3	N1	5	-152.48 s	30.0 kHz	-3.64 dB		
Scan	D4	N1	5	-146.9 s	-30.0 kHz	-11.85 dB		
Scan	N5		5	-164.63 s	33.24 MHz	43.49 dBµV/m		

(a)



Diagr	Type	Ref	Trc	Frame	Stimulus	Response	Function	Function Result
Scan	N1		1	0.0 s	41.19 MHz	48.28 dBµV/m		
Scan	D1	N1	5	-32.17 s	0.0 Hz	0.00 dB		
Scan	D2	N1	5	-227.2 s	0.0 Hz	-8.42 dB		
Scan	N3		5	-147.78 s	33.69 MHz	42.90 dBµV/m		

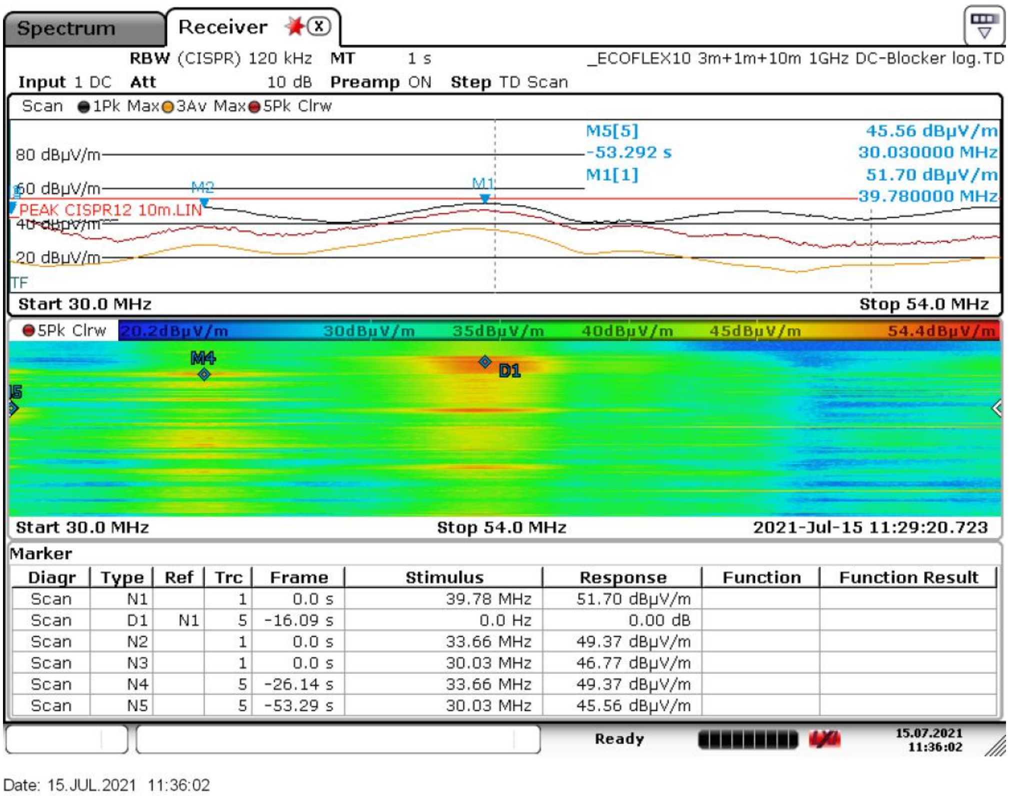
(b)

Source: JRC, 2021.

5.1.6 Regenerative braking

This measurement was realized in order to investigate any potential effects of a different setting on the deceleration phase for EMIs. Indeed, the vehicle was set with level 3 of recuperation (maximum level of recuperation during regenerative braking) and the driving mode was selected as ECO.

Figure 22. Spectrogram referred to the frequency range 30 – 54 MHz. The vehicle is placed with its left side versus the antenna (V-pol), driven in ECO + mode following customized driving cycle of stepped speeds (0-40-60-80-100-120 km/h);



Source: JRC, 2021.

Figure 22 shows the spectrogram of the frequency range 30 – 54 MHz recorded with the vehicle placed with its left side versus the vertically polarized antenna, following customized driving cycle of stepped speeds (0-40-60-80-100-120 km/h).

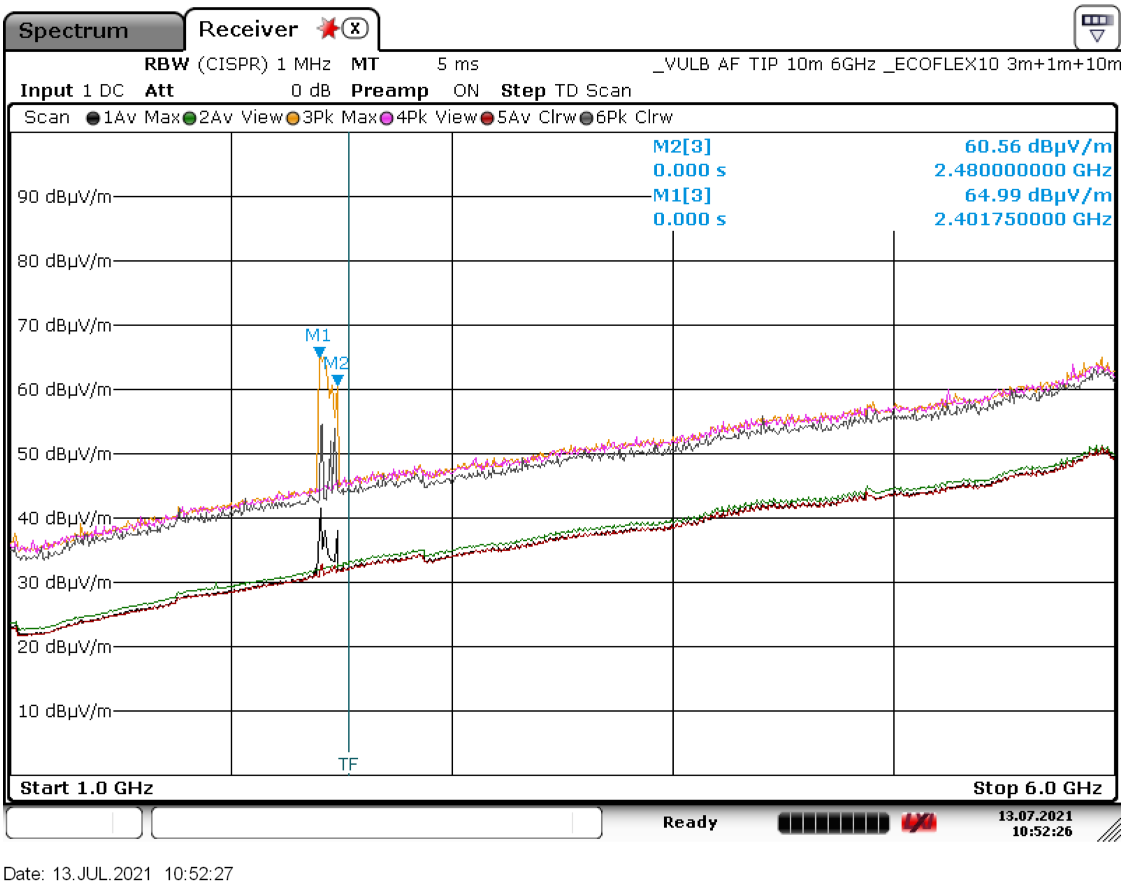
The highest peak appeared at 39.78 MHz with amplitude of 51.70dBµV/m during the deceleration phase. A value of 49.37dBµV/m was reached at 33.66 MHZ in correspondence of the beginning of the deceleration. Amplitude of 45.56dBµV/m was recorded at 30.03 MHz during the acceleration from 100 km/h to 120 km/h.

The results of this test are comparable with those obtained for the test conducted without the level of recuperation in place.

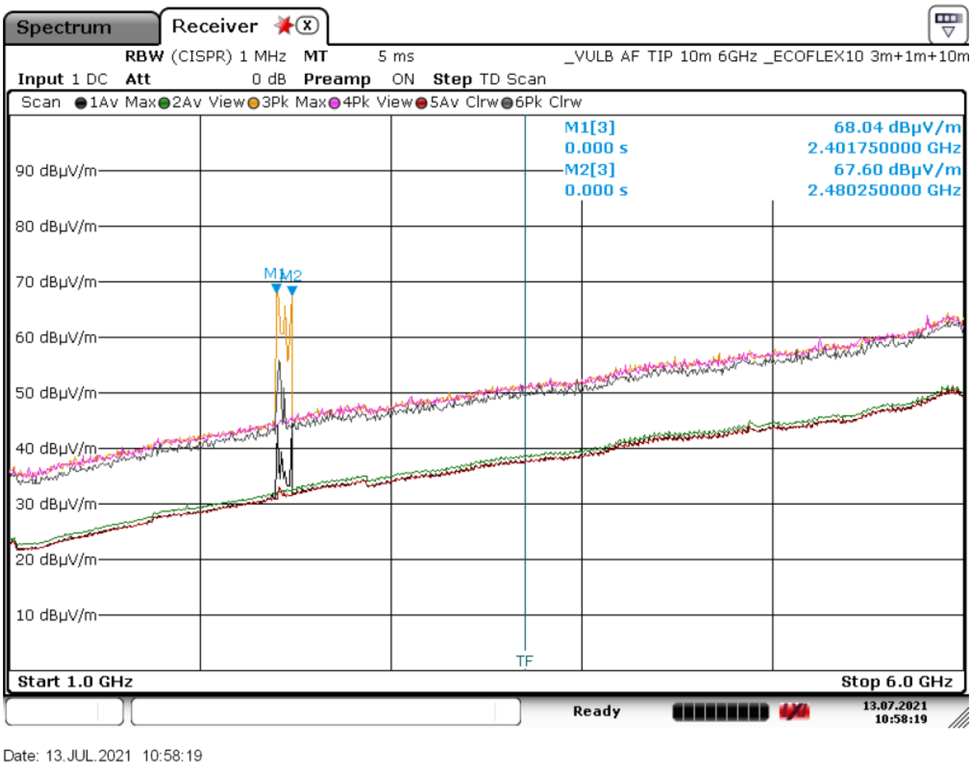
5.2 1 GHz – 6 GHz

The 360-degrees rotation of the turntable was used to scan the frequency range 1 – 6 GHz. The EMI receiver was set with a resolution bandwidth of 1 MHz and with the peak detector. Two measurements were performed at the constant speeds of 40 km/h and 100 km/h for each antenna polarization in ECO mode (Figure 23, Figure 24). EMIs at 2.48GHz and 2.4 GHz were recorded in all four measurements with the amplitude of around 60dBμV/m. The worst case was recorded for the vertical polarization with the vehicle driven at a constant speed of 120 km/h: significant EMIs were observed at 2.4 GHz (68.04dBμV/m) and at 2.48 GHz (67.6dBμV/m).

Figure 23. 360 degrees rotation, ECO mode, V-pol, 40 km/h (a), 100 km/h (b).



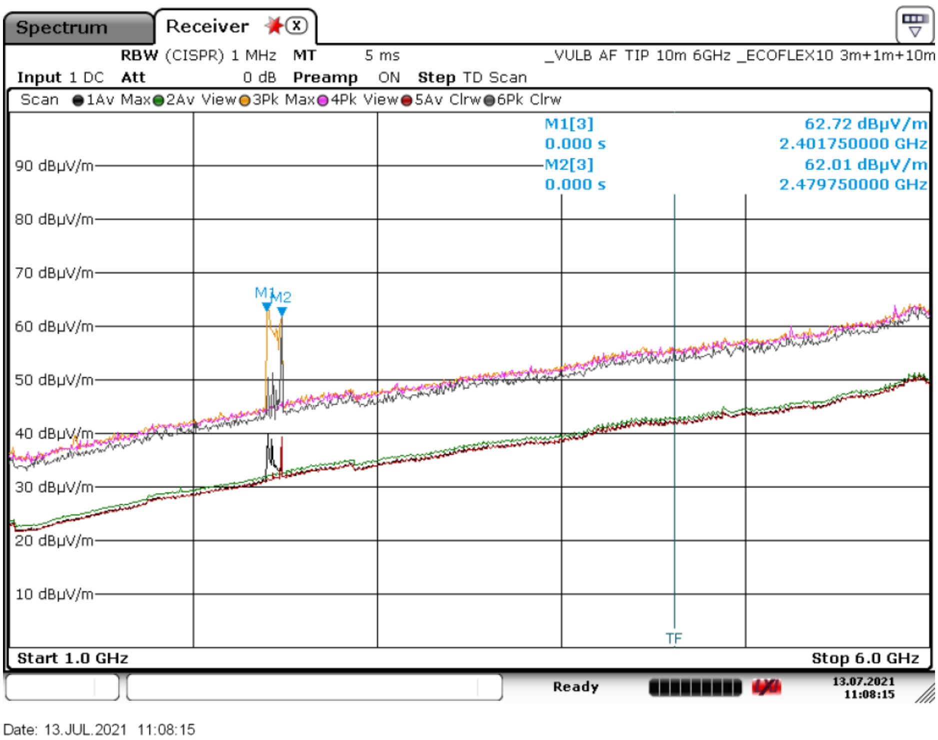
(a)



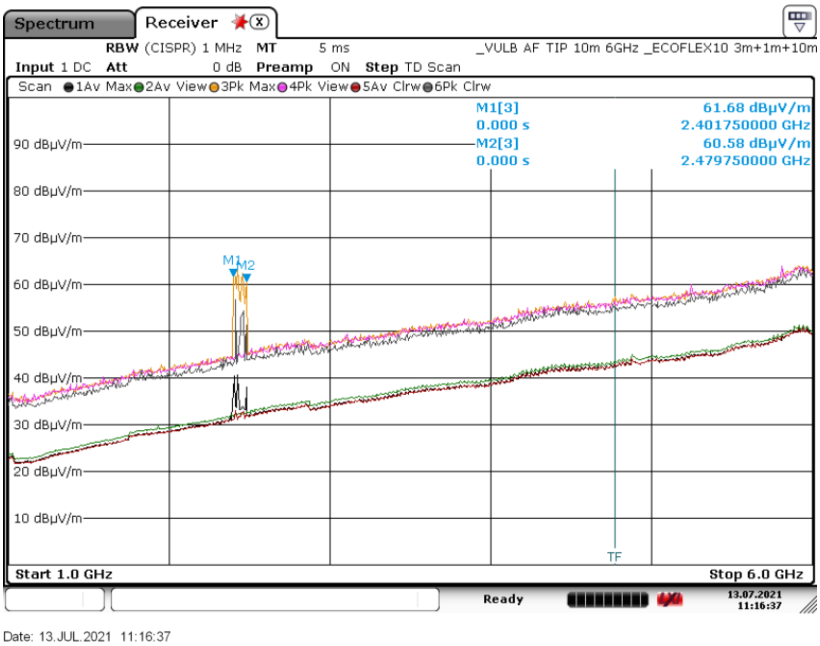
(b)

Source: JRC, 2021.

Figure 24. 360 degrees rotation, ECO mode, H-pol, 40 km/h (a), 100 km/h (b).



(a)

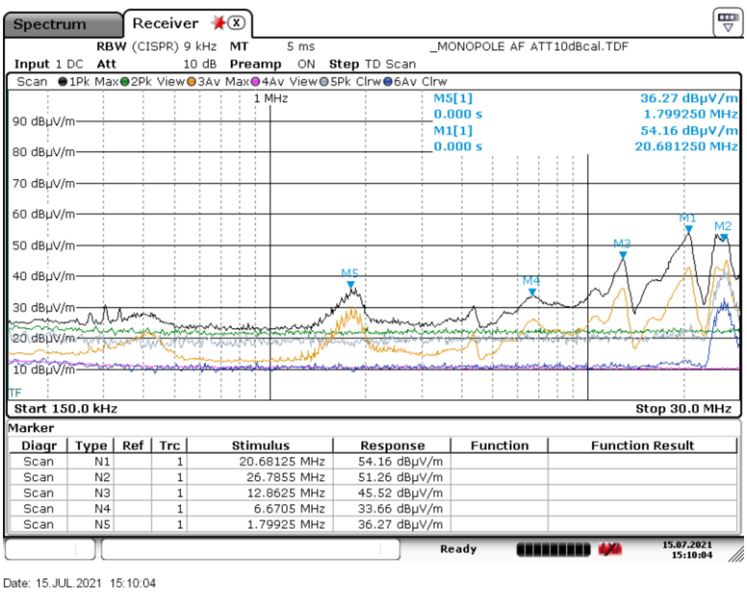


b)

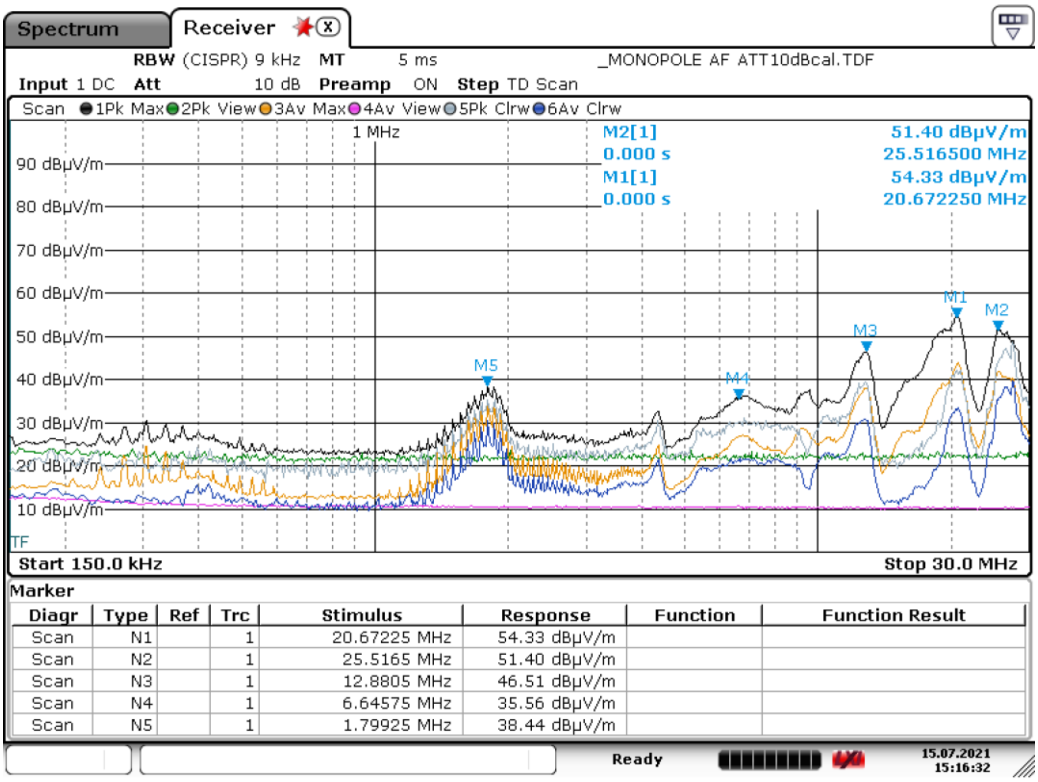
5.3 150 kHz – 30 MHz

The frequency range 150 kHz – 30 MHz was scanned with the 360-degrees rotation of the turntable and using the monopole antenna. The EMI receiver was set with a resolution bandwidth of 9 kHz and with the peak detector. Measurements were performed at different constant speeds (40, 60, 80, 100, 120 km/h, respectively a, b, c, d, e) in Normal mode with the antenna vertically polarized. EMIs were recorded around 20, 26, 12, 6, and 1.79 MHz. The amplitude of the disturbance at 26 MHz increases together with the speed, as it is possible to see in Figure 25. Indeed, at 40 km/h its value is of 51.26 dBµV/m (a), while at 120 km/h is 56.30 dBµV/m (b).

Figure 25. 360 degrees rotation, V – pol, Normal mode at different constant speeds of 40 (a), 60 (b), 80 (c), 100 (d) and 120 km/h (e).



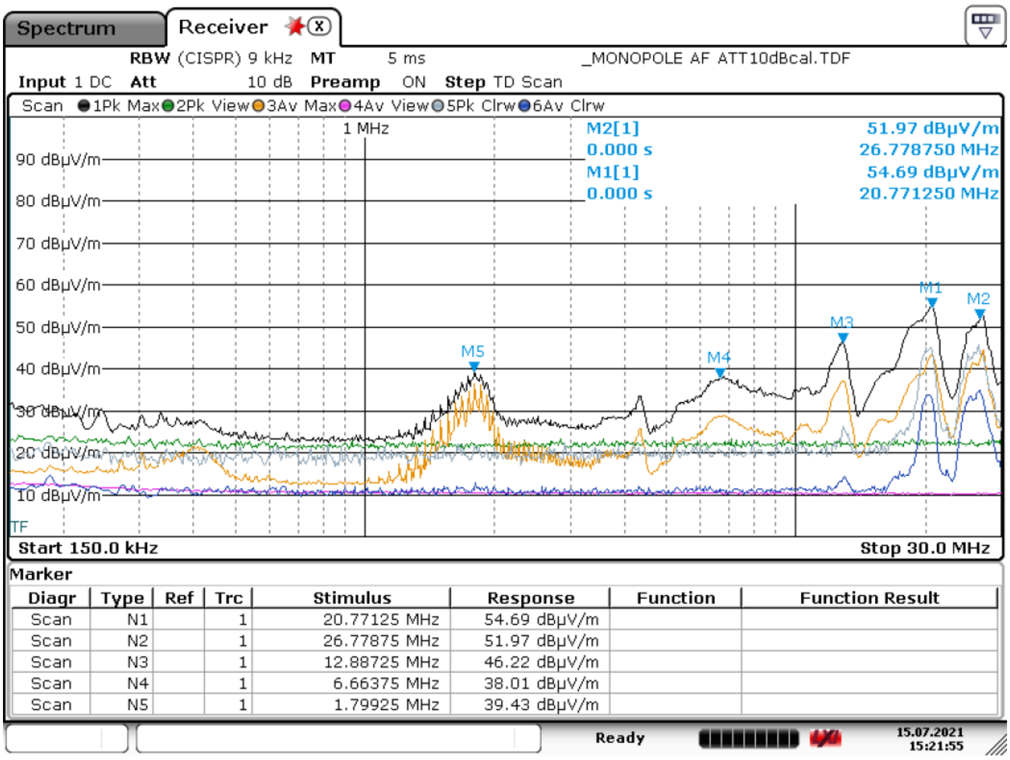
(a)



Diagr	Type	Ref	Trc	Stimulus	Response	Function	Function Result
Scan	N1		1	20.67225 MHz	54.33 dBµV/m		
Scan	N2		1	25.5165 MHz	51.40 dBµV/m		
Scan	N3		1	12.8805 MHz	46.51 dBµV/m		
Scan	N4		1	6.64575 MHz	35.56 dBµV/m		
Scan	N5		1	1.79925 MHz	38.44 dBµV/m		

Date: 15.JUL.2021 15:16:32

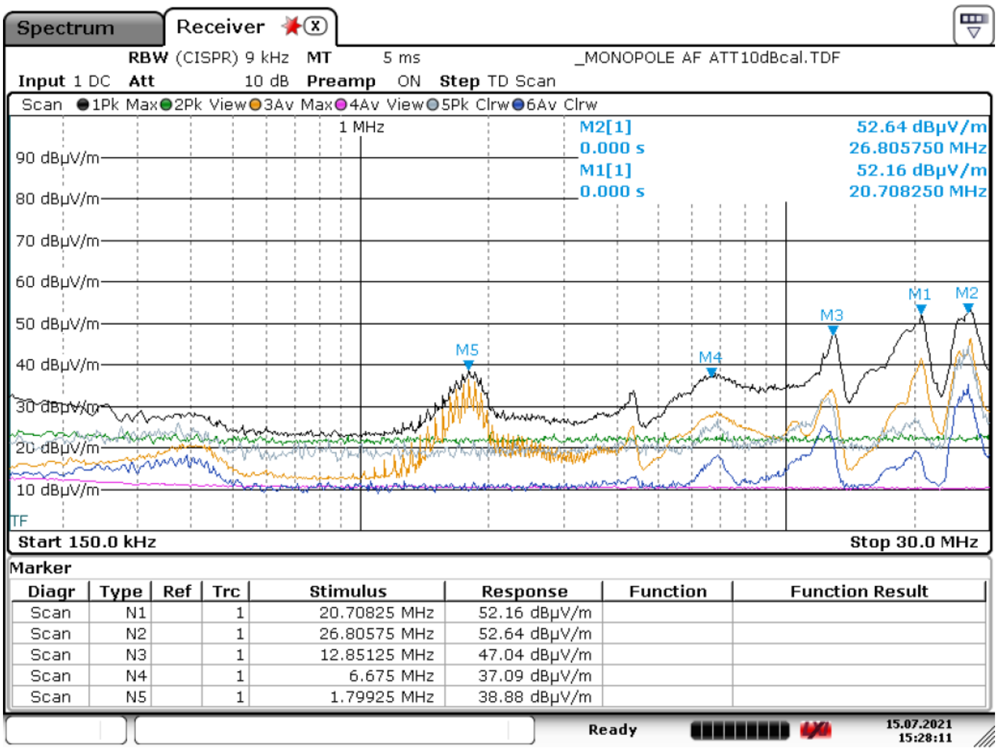
(b)



Diagr	Type	Ref	Trc	Stimulus	Response	Function	Function Result
Scan	N1		1	20.77125 MHz	54.69 dBµV/m		
Scan	N2		1	26.77875 MHz	51.97 dBµV/m		
Scan	N3		1	12.88725 MHz	46.22 dBµV/m		
Scan	N4		1	6.66375 MHz	38.01 dBµV/m		
Scan	N5		1	1.79925 MHz	39.43 dBµV/m		

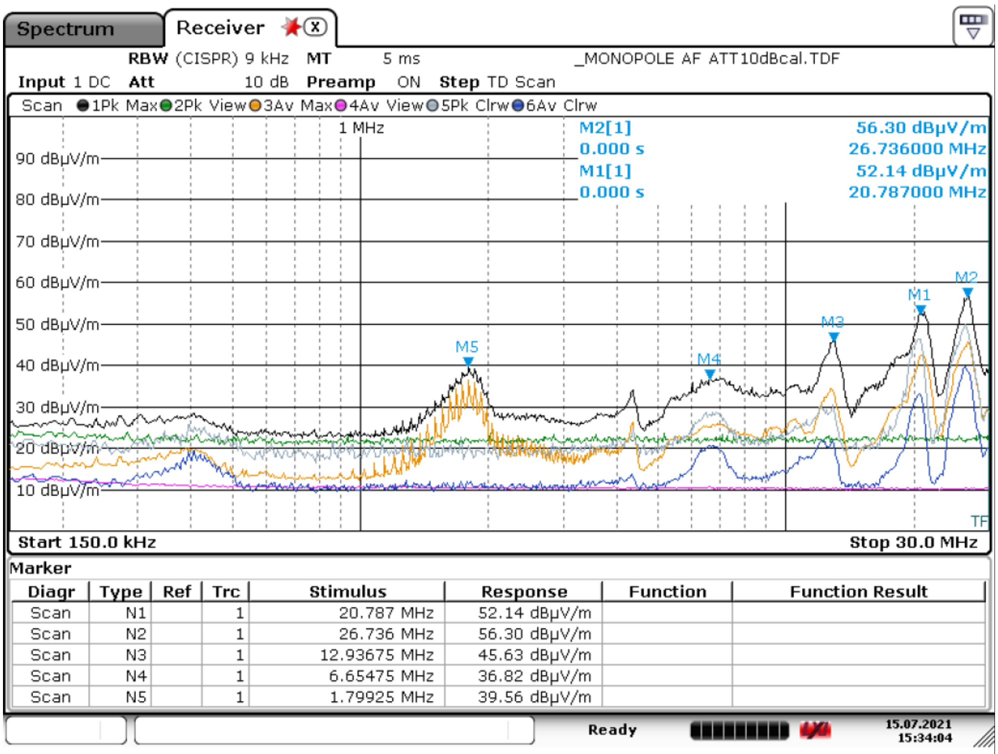
Date: 15.JUL.2021 15:21:56

(c)



Date: 15.JUL.2021 15:28:12

(d)



Date: 15.JUL.2021 15:34:04

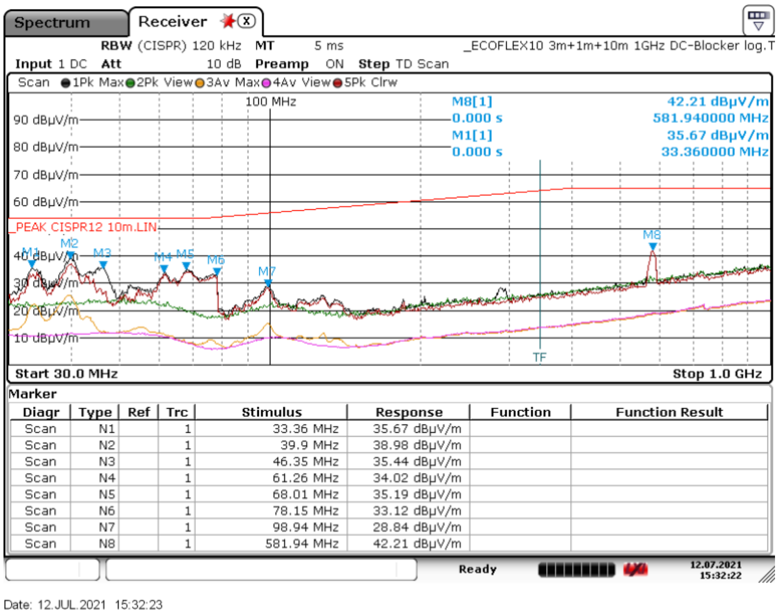
(e)

Source: JRC, 2021.

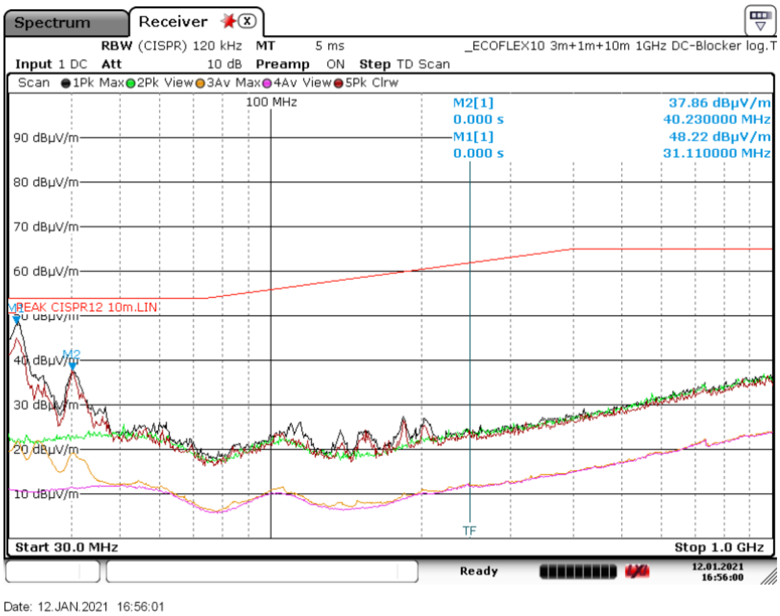
5.4 The impact of invasive interventions

Invasive interventions were realized to prepare the vehicle for on - road tests. Protections were removed in order to reach sample points that were opportunely shielded and protected. This resulted in a marked deterioration of the vehicle EMC behaviour. As it can be seen in Figure 26, Figure 27, Figure 28 and Figure 29, peaks at frequency around 31 MHz were close to the limit even at a constant speed of 40 km/h for the left and right positions. They were above the limit with values of 61.09dBμV/m and 62.46dBμV/m for the rear and the front positions respectively.

Figure 26. Vehicle driven in ECO mode at a constant speed of 40 km/h, and positioned with its left side versus the V – pol antenna (a), with invasive interventions (b).



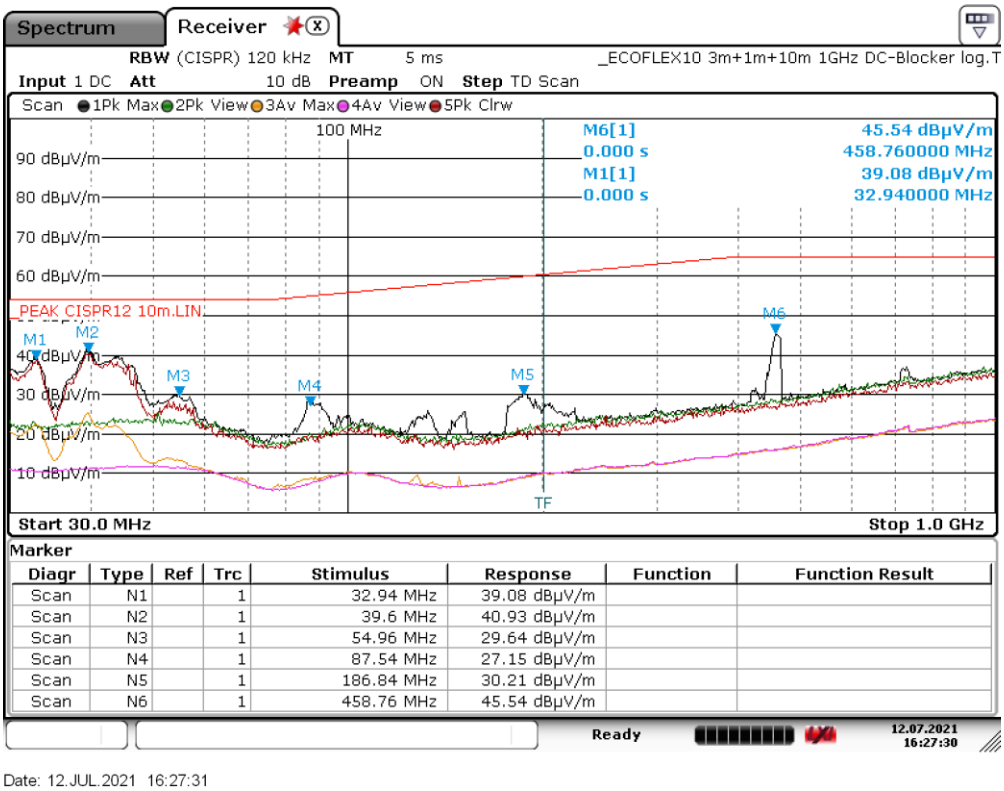
(a)



(b)

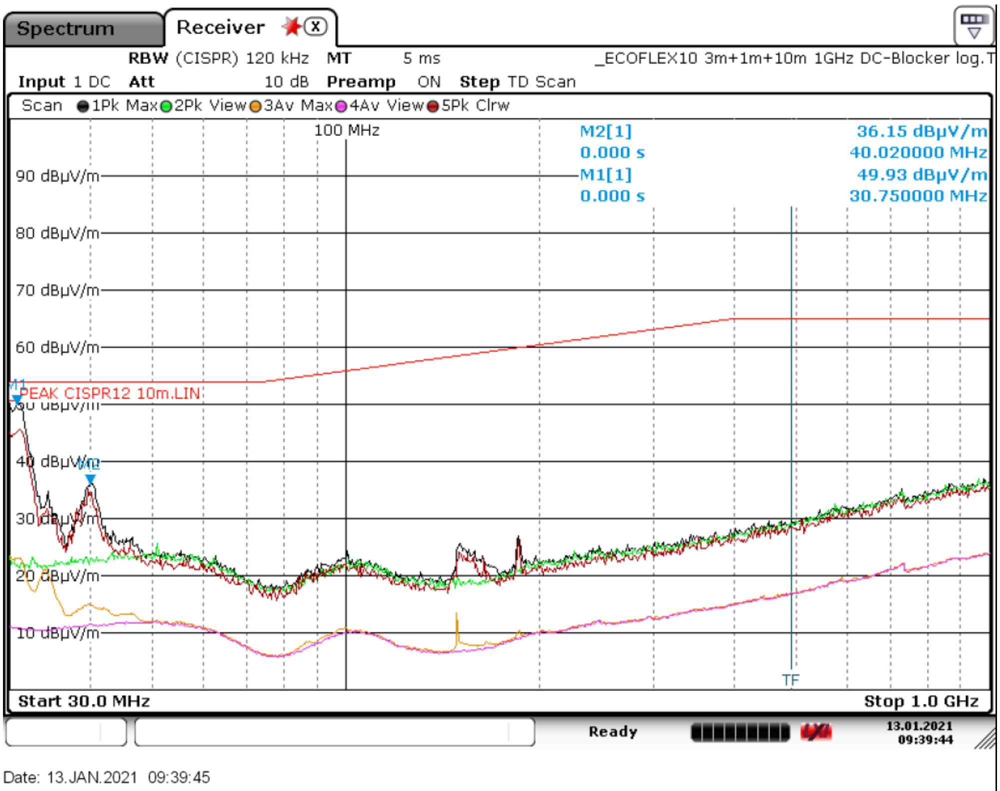
Source: JRC, 2021.

Figure 27. Vehicle driven in ECO mode at a constant speed of 40 km/h, and positioned with its right side versus the V – pol antenna (a), with invasive interventions (b).



Diagr	Type	Ref	Trc	Stimulus	Response	Function	Function Result
Scan	N1		1	32.94 MHz	39.08 dBµV/m		
Scan	N2		1	39.6 MHz	40.93 dBµV/m		
Scan	N3		1	54.96 MHz	29.64 dBµV/m		
Scan	N4		1	87.54 MHz	27.15 dBµV/m		
Scan	N5		1	186.84 MHz	30.21 dBµV/m		
Scan	N6		1	458.76 MHz	45.54 dBµV/m		

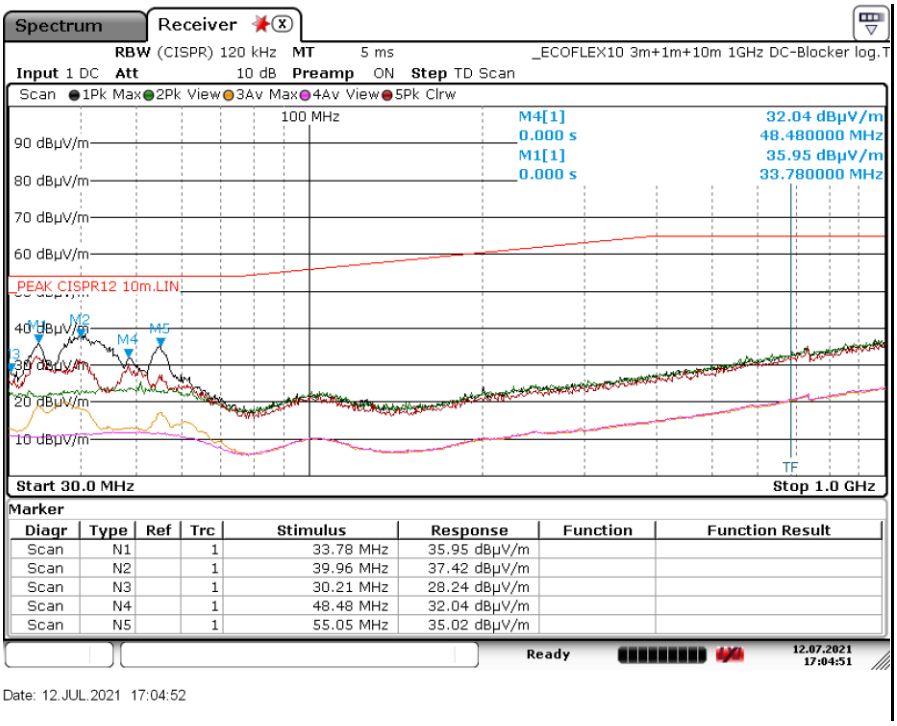
(a)



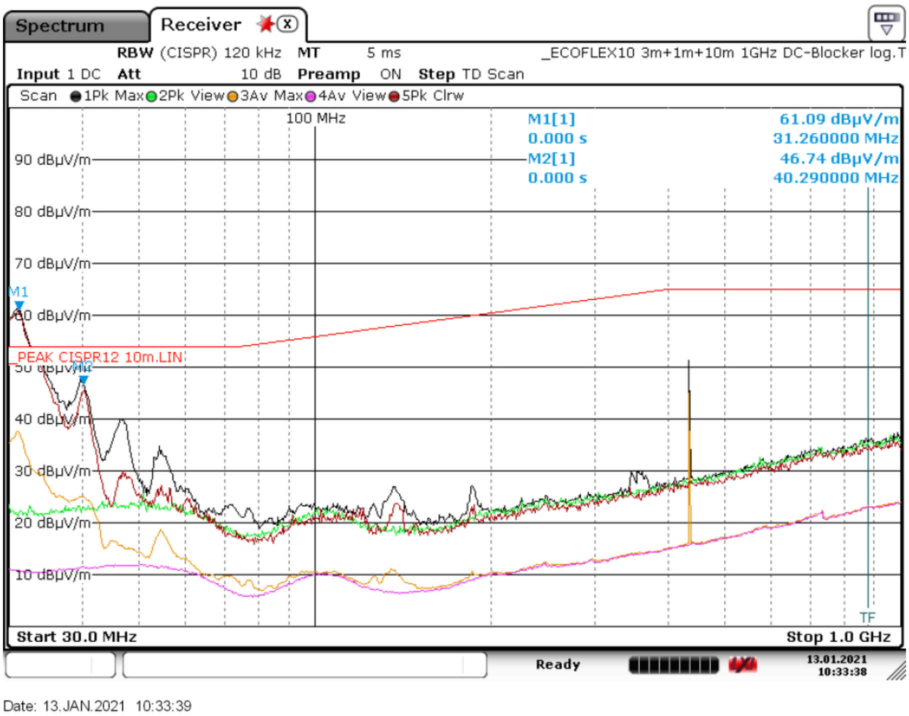
(b)

Source: JRC, 2021.

Figure 28. Vehicle driven in ECO mode at a constant speed of 40 km/h, and positioned at the rear of the V – pol antenna (a), with invasive interventions (b).



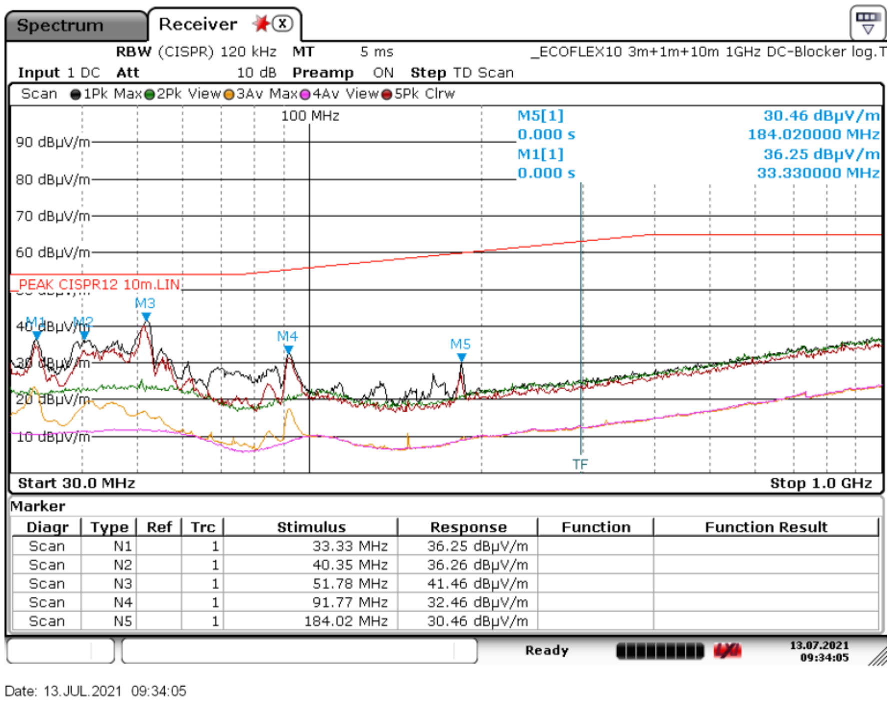
(a)



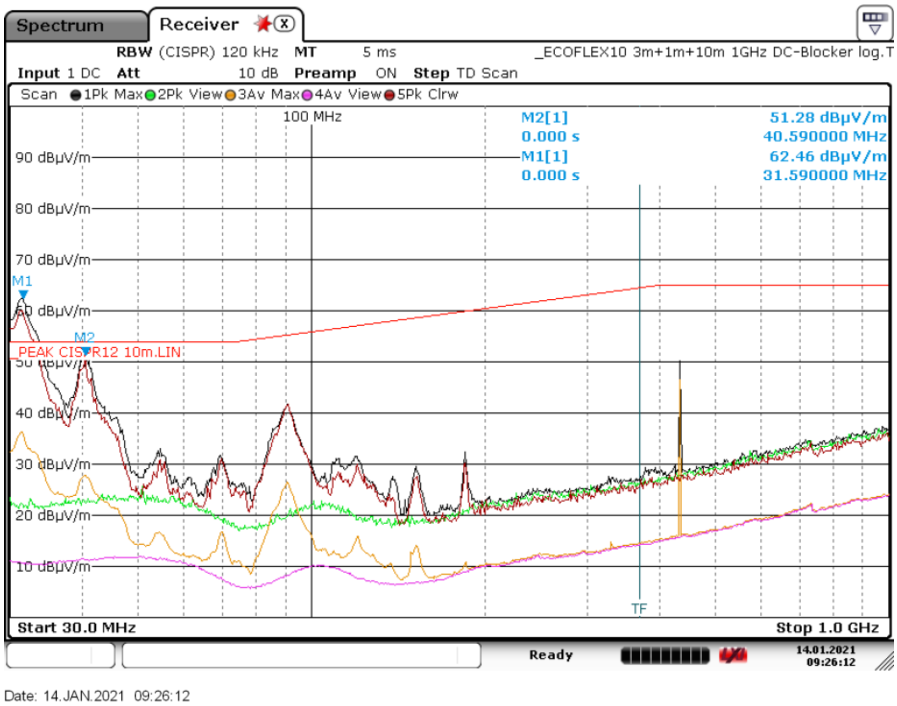
(b)

Source: JRC, 2021.

Figure 29. Vehicle driven in ECO mode at a constant speed of 40 km/h, and positioned with its front versus the V – pol antenna (a), with invasive interventions (b).



(a)



(b)

Source: JRC, 2021.

6 Conclusions

This technical report shows the results of the first EMC test campaign realized with a fuel cell vehicle within Vela9. The impact of different tested sides of the vehicle, driving modes, constant speeds and driving cycles (stepped accelerations and decelerations) on the generated radiated emissions was investigated. The in-use test protocol followed the requirements of Regulation n.10, but it included also other types of measurements to overcome some limits of the Regulation and to provide a full characterization of disturbances emitted by the vehicle during dynamic driving conditions. It is worth to underline that recorded radiated emissions were in all measurements compliant with the CISPR12 limit settled in Regulation n.10.

Results showed that the left side of the vehicle was slightly worse in terms of radiated emissions compared to the right side. Likewise, the front side emitted more disturbances compared to the rear position. This result was also confirmed by the spectrograms within the frequency range 30-54 MHZ. Tests at constant speed indicated that Normal mode generated more disturbances compared to the ECO mode. For this reason, spectrogram analysis was conducted in Normal mode.

Spectrogram analysis was performed to deeply investigate the frequency range 30-54MHz, which resulted to be the most critical within the whole frequency range. Critical frequencies at 33 MHz, 39 MHz, 46 MHz were observed regardless the position of the vehicle and for most of them it has been found a dependency between field strength and speed change.

During the test where a stepped driving cycle was followed, the critical frequency of 39 MHz reached an E-field strength value of 52.47dBµV/m at the end of the driving cycle when the vehicle reached 0 km/h. A peak of 50.8dBµV/m was recorded at the frequency of 30 MHZ when the vehicle was driven a constant speed of 120 km/h. In addition, once identified critical frequencies, the time domain analysis was conducted aligning speed data from the dyno roller benches with data from the receiver. For the frequency of 39 MHz, the time domain analysis showed that the battery might contribute to reduce the amplitudes of EMIs. In fact, when a constant speed was reached, only the fuel cell was in charge of the traction. For the time domain analysis at 30 MHz, disturbances went up as the speed increased and they reached higher values at a speed of 120 km/h. This confirmed the correlation for electrified vehicles between EMIs and the increase of speed for frequency at 30 MHz. This has already been observed in previous scientific test campaigns.

Furthermore, the turntable allowed for the identification of the worst position in terms of radiated emissions even when frequency ranges not foreseen within the Regulation were scanned. Frequency ranges 1 – 6 GHz and 150 kHz – 30 MHz were explored registering disturbances at 2.48GHz and 2.4 GHz and 20, 26, 12, 6, and 1.79MHz. The amplitude of the disturbance recorded at the frequency of 26 MHz was 56.30dBµV/m, at a speed of 120 km/h.

Specific conditions were also considered, such as the case of road loads not inserted within the dyno roller bench software, the case of the selection of the highest level of regenerative braking in the ECO + driving mode and the impact of invasive interventions on the vehicle. In the first case this condition did not influence the frequencies at which EMIs appeared and their amplitude. When the third level of regenerative braking was selected, EMIs appeared substantially at the same frequencies and with the same amplitude than previously observed for the test conducted without any extra level of regenerative breaking. Finally, in the case of invasive interventions, made to perform on-road testing, the EMC performances of the vehicle were deteriorated. Values above the limit, of 61.09dBµV/m and 62.46dBµV/m were recorded for the rear and the front sides respectively even at speeds of 40 km/h. This underlines the importance to perform EMC test on vehicle without any kind external modification compared to the origin condition of the EuT.

To conclude, this test campaign confirms the reliability of the developed EMC protocol also when the vehicle under test is a fuel cell vehicle. Measurements under more realistic driving conditions allowed finding out EMC behaviors, otherwise unknown.

References

ETS-Lindgren, '3301C Active Monopole Datasheet', 2017. http://www.ets lindgren.com/products/antennas/rods/4010/401001.

IEC, *CISPR 12:2001 Vehicles, Boats and Internal Combustion Engines - Radio Disturbance Characteristics - Limits and Methods of Measurement for the Protection of off-Board Receivers 5th Edition*, 2001.

Pliakostathis, K., M. Zanni, G. Trentadue, and H. Scholz, 'Vehicle Electromagnetic Emissions: Challenges and Considerations', *EMC Europe 2019 - 2019 International Symposium on Electromagnetic Compatibility*, 2019.

Pliakostathis, K., M. Zanni, G. Trentadue, H. Scholz, H.D. Kluge, M. Frankholz, L. Sauer, et al.., *Electromagnetic Compatibility (EMC) Evaluation of a Prototype Solar- Charged Electric Race-Car*, EUR 29991 EN, Publications Office of the European Union, Luxembourg, 2019, doi:10.2760/379632.

Pliakostathis, K., M. Zanni, G. Trentadue, and H. Scholz, 'Assessment of a Vehicle's Electromagnetic Emissions under Dynamic Drive Conditions', *IEEE Transactions on Electromagnetic Compatibility*, Vol. 62, No. 6, 2020, pp. 2411–2422.

Pliakostathis, K., M. Zanni, G. Trentadue, and H. Scholz, *Preliminary Investigation of the Electromagnetic Compatibility (EMC) of a Mini-Car Electric Vehicle*, European Union 2018.

Rohde & Schwarz Systems Support Center, *EMI Measurements , Test Receiver vs Spectrum Analyzer*, n.d.

Schwarzbeck Mess-Elektronik, *VULB 9162*, Vol. 920, Vol. 920, n.d.

UNECE, 'Addendum 9: Regulation No. 10 Revision 4 - Amendment 1', Vol. 1958, No. March 1958, 2012.

List of abbreviations and definitions

AC/DC Alternated Current/Direct Current

BHDC high voltage battery DC converter

CISPR Comité International Spécial des Perturbations Radioélectriques (English: International Special Committee on Radio Interference)

CoC Certificate of Conformity

DC Direct Current

EMF Electro-Magnetic Field

EMC Electro-Magnetic Compatibility

EuT Equipment under Test

EMI Electro-Magnetic Interference

FCEV Fuel cell electric vehicles

FFT Fast Fourier Transform

H-pol Horizontal Polarization

JRC Joint Research Centre

LDC Low Voltage DC Converter

PEM Proton Exchange Membrane

RE Radiated Emissions

VeLA Vehicle Electric Laboratory

V-pol Vertical Polarization

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