A Test Setup to Assess the Impact of EMI Produced by On-Board Electronics on the Quality of Radio Reception in Vehicles

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Abstract*—Radio performance is very important in the automotive industry. It is necessary to provide a careful assessment of radio reception of each vehicle project development. It is well known that the vehicle radio performance may be affected by electromagnetic interferences from the components of the vehicle itself. These interferences degrade the radio signals and prevent the on-board receiver from retrieving correctly the baseband signal. Generally, the car manufacturers rely on the international special committee on radio interference (CISPR) 25 standard to decide whether radio reception tests pass or fail according to the interference limits set in advance. However, although the standard is able to detect interferences and determine their type and level according to various detectors, their consequence on radio reception quality (if any) cannot be assessed in a quantitative manner. This is even more difficult with digital communication systems such as digital analog broadcasting (DAB). For the time being, the final quality of the radio reception is evaluated in a totally independent way, through driving tests. This paper introduces an improved test setup that performs both interference level measurements and assessment of the radio reception performance. Two operating modes are described. They are based either on the conducted or the radiated injection of the transmitted radio signal. Although dedicated to analog and digital transmissions, we will deal only with the analog radio (frequency modulation) in this paper. From a set of experiments, we conclude that interferences measured with average detectors are more likely correlated to radio reception issues.

Index Terms*— EMC, RF, Radio-reception, Vehicle radio, CISPR 25, modulation, interference, noise, audio, automotive, FM, AM, DAB, anechoic chamber, SNIR (signal to noise and interference ratio), degradation sensitivity.

I. Introduction

THE electronic components of vehicles produce electromagnetic interferences. These interferences may degrade the radio signal modulated in the amplitude modulation (AM), frequency modulation (FM) and DAB bands [1], [2], [3], and thereafter the quality of the audio listening [4]. However, it is possible to measure the level of interference (peak, average and quasi-peak values) at the output of the antenna cable according to CISPR 25 standard [5].

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Nevertheless, there is no clear relationship between the recorded levels of interferences, whether below or above the prescribed limits, and the consequences with regards to the possible degradation of the analog or digital radio reception quality.

Moreover, the prescribed detectors and dwell times of CISPR 25 provide a clear picture of permanent interferences or transient interferences at high repetition rates but are not reliable for interferences with low repetitive frequency or intermittent ones such as for electric controlled mirrors, electric window up/down maneuvers…The current radio listening driving assessment methods and analysis only provide a possible classification of listening degradation but is hardly associated with interferences produced on-board vehicles at the same instant. In the literature, there are several methods for evaluating the radio reception but they have all limitations. For example, some methods require an assessor in charge of classifying the listening quality and the test set-up uses an audio receiver outside the test chamber that does not allow taking into account other sources of disturbances such as conducted emissions on the harness of the real radio receiver in the vehicle [6]. The patent [7] does not enable tests in different polarizations of the incident field (only vertical polarization in a transverse electromagnetic (TEM) cell for instance and does not describe a method to connect and drive the in–situ car radio without introducing other disturbances (non-intrusive). Other methods explore different waveforms or types of interferences using an artificial interference source, and the elaboration of the test radio are on table [8], [9]. This does not allow the analysis of the on-board interference signals. Furthermore, some articles propose a hardware modification of the vehicle receiver (such as the installation of a digital filter to reduce disturbances [10], [11], [12], but the manufacturers do not have the access to the receiver's algorithm). Finally, some authors suggest using numerical simulation for evaluating the radio receiver performance [13]. Establishing a cause-to-effect relationship between audio listening and interference measurements is a key issue. An improved test setup is required, addressing radio reception performance in practically the same exact conditions that would enable further investigations according to CISPR 25 measurements, in case of degradation of the quality of reception. To our best knowledge, among various proposals in the open literature, no test set-up, by itself, provides a comprehensive response for that issue.

The principle consists in installing the vehicle under test (VUT) in a semi-anechoic chamber including also a laboratory radio transmitter to simulate a broadcasting (AM, FM, DAB…)

transmitter. Its power level is adjusted while measuring the SNIR (signal-to-noise plus interference ratio) in the baseband signal at the audio output of the car radio. Note that we use a single-tone modulating signal for audio analysis and therefore SNIR estimation, although more sophisticated metrics exist according to international telecommunication union (ITU) standards [14]. The reception threshold or sensitivity threshold is determined as the minimum (voltage or electric field) level above which the radio receiver can correctly demodulate a radio signal. To perform such a measurement, it is necessary to design a proper instrumentation chain to couple the receiver output to an audio analyzer.

This test setup is then used to record the sensitivity threshold modification induced by on-board vehicle interferences. There are two variants of the test configurations. On the one hand, the transmitter signal is radiated in the semi-anechoic chamber and received by the car receiver antennas. On the other hand, the radio signal is electrically coupled to the car radio receiver input. These two variants will be called respectively radiated and conducted modes in the rest of this paper.

The article is organized as follows. In section II, we briefly describe the interference measurement process and raise the key issues about this way of assessing the radio reception. In section III, we introduce and detail the principle of our improved test setup. It is dedicated to the measurement method of the sensitivity threshold in the radiated mode of the associated test setup, whereas section IV describes the conducted mode procedure. Furthermore, section V provides a cross-validation of both procedures. Finally, Section VI discusses about the non-systematic correlation between the interference levels and the sensitivity thresholds. The last section concludes and brings perspectives to this work.

II. INTERFERENCE MEASUREMENTS AT THE INPUT OF A CAR RADIO

The CISPR 25 standard describes the method of measuring the interference voltage at the end of the vehicle antenna cable (on the receiver side) in the radio bands (AM, FM, DAB). In this section, we provide an example of an interference analysis measured at the input of the car radio according to this standard. The objective is to examine, on the one hand, the repeatability (over time) of the measurements of the interferences generated by the vehicle in the FM band, and, on the other hand, whether it is possible to distinguish between transient and permanent disturbances. Transient interferences are periodic signals with high repetition rate such as those associated to electronic control unit clocks or other periodic signal with smaller repetition frequency. Permanent interferences are broadband, non-periodic interferences (e.g. ignition system) and also include intermittent interferences.

To do so, we perform interference measurements using peak (PK) and average (AVG) detectors as defined in the CISPR 25 standard.

A. Interference measuring method according to CISPR 25

To carry out these measurements, the VUT must be placed in a semi-anechoic chamber. An electromagnetic interference (EMI) receiver (with an RF preamplifier) is required to measure the interference voltage at the output of the vehicle antenna cable. Furthermore, the output of the antenna cable (on the car radio side) must be connected to the RF measurement cable as depicted in Fig. 1.

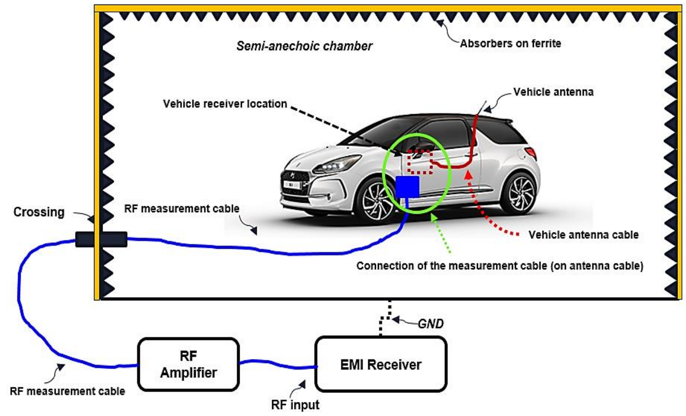

Fig. 1. Overview of the interference measurement according to CISPR 25 standard.

B. Interference measurement results

In this part, we present the results of interference measurements at the output of the antenna cable with AVG and PK detection in the FM band. In a first step, we have first established a measurement of AVG ambient noise (background noise) in the semi-anechoic room. In a second step, we have carried out three successive measurements while the VUT engine was running.

As shown in Fig. 2, the three successive measurements of interference in AVG mode overlap perfectly. Significant levels of induced voltage appear at 96 MHz, 99 MHz and 100 MHz. These type of interferences are generally created by the clocks of the vehicle’s electronic components which explain the repeatability of the measurements in this case.

In this paper, all the tests have been carried out on an Internal Combustion Engine (ICE). The PK measurements of the vehicle's interference, in the same experimental conditions, are presented in Fig. 3 (a, b).

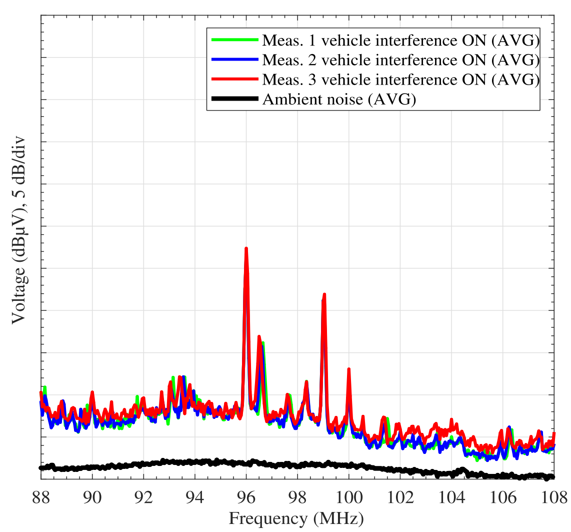

Fig. 2. Three different AVG measurements at the car radio receiver input. The black curve indicates the ambient noise.

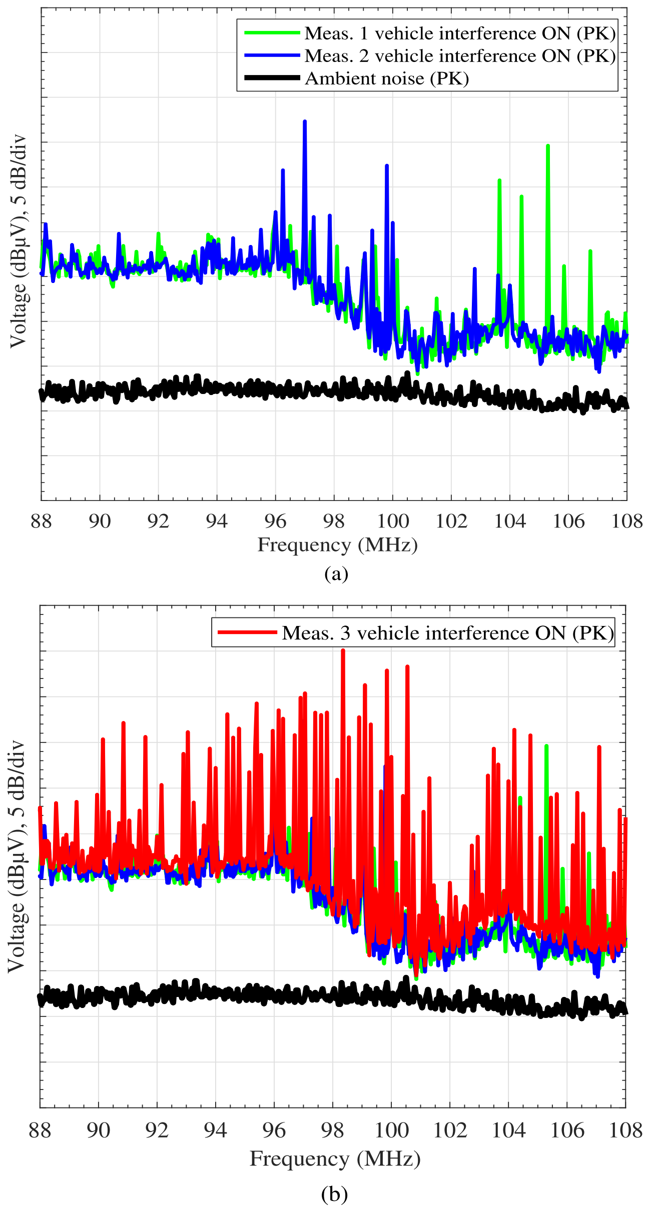

Fig. 3. Three different PK measurements at the car radio receiver input. The black curve corresponds to the ambient noise.

Fig. 3 shows all three PK measurements taken successively. In Fig. 3a we have plotted two interference measurements. In Fig. 3b we have simply added a third interference measurement. It does not come to a surprise that PK measurements are not repeatable due to the limited dwell time (DT). The detection of low repetition rate of transient or intermittent signals has a probability of detection that is inversely proportional to this rate. In other words, the average detection partly removes this effect and appears to be more repeatable. It turns out that, with regard to the identification of possible causes of audio quality degradation, other types of detectors (e.g. quasi-peak detector) may be used for further investigations. Nevertheless, PK and AVG detectors provide an interesting initial observation and remain used throughout this paper. Nevertheless, various detectors may be used for practical investigations on the source of the detected interference.

From these results, several questions arise: Should we base our analysis on PK or AVG measurements to assess the impact of interferences on radio reception? In particular, PK measurements reveal that on-board interferences include instantaneous variations that are detected in the prescribed limited dwell time (10 ms per frequency) of the EMI receiver. One can hardly foresee the impact of such transient phenomena on radio reception. Such impact is likely to be different according to digital or analog broadcasting. Moreover, in case the level of interferences, in PK or AVG detection mode, exceeds the limits defined by the car manufacturer, is it sufficient to conclude that the radio listening is impacted?

The method exposed in this paper aims at identifying any causal relation between on-board interferences and degradation of listening conditions. The following sections are dedicated to a detailed description of a test setup for the radiated and conducted modes, and to the demonstration of its operational principle. The last section of this work provides some answers to the previous questions, based on experiments carried out with this test setup.

III. A TEST SETUP FOR THE QUALITY ASSESSMENT OF RADIO RECEPTION RELATED TO INTERFERENCES: THE RADIATED MODE

The proposed method is an indoor evaluation method of radio reception. As described in Fig. 4, a radio signal is transmitted in the semi-anechoic chamber using a laboratory radio transmitter. A given SNIR threshold is defined to decide on pass or fail of listening conditions. This will correspond to the sensitivity threshold of the car receiver.

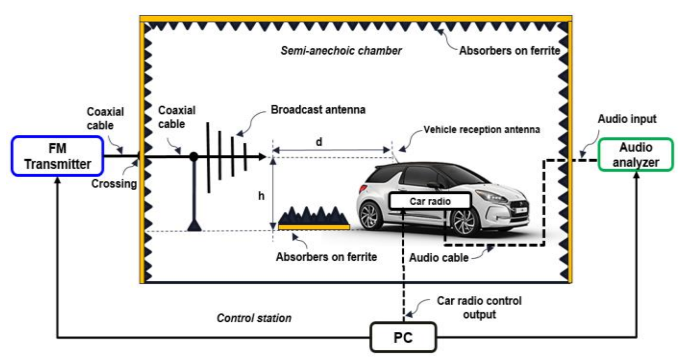

Fig. 4. Test setup of the sensitivity threshold measurement in a semi-anechoic chamber.

As far as the radiated mode operation is concerned, the radio signal is transmitted using a log-periodic antenna. The sensitivity threshold is related to the incident electric field strength level at the position of the vehicle's receiving antenna.

A. Sensitivity threshold (in terms of incident electric field) measurement method

In this section, we detail the procedure to measure the sensitivity (S_{EI}) of the vehicle expressed as the minimum required incident electric field level at the receiving antenna position in the FM band allowing the FM receiver to correctly produce the audio signal. To do so, it is necessary to vary the power level of the FM transmitter while measuring the SNIR (by means of an audio analyzer) of the demodulated audio signal. We had to first define the acceptable level of SNIR, or reciprocally the ratio of acceptable noise that would correspond to the transition from an audible signal to a non-audible signal. To do this, we plotted the noise ratio as a function of the modulated signal input power. According to Fig. 21 in Appendix A, the amount of noise at the audio analyzer exhibits an abrupt transition within a few dB of power input variations. From these curves, we estimated that the noise to signal ratio must remain below 2 % (SNIR= 50 or 17 dB).

Thus, the test consists in increasing the power of the transmitter until this threshold is reached. The corresponding electric field level represents the actual sensitivity threshold. This operation is repeated for every required frequency of analysis in the FM band.

The Fig. 5 provides a detailed representation of the test setup for the S_{EI} measurement. The test environment is composed of the semi-anechoic chamber, the VUT and finally the control room of the test setup.

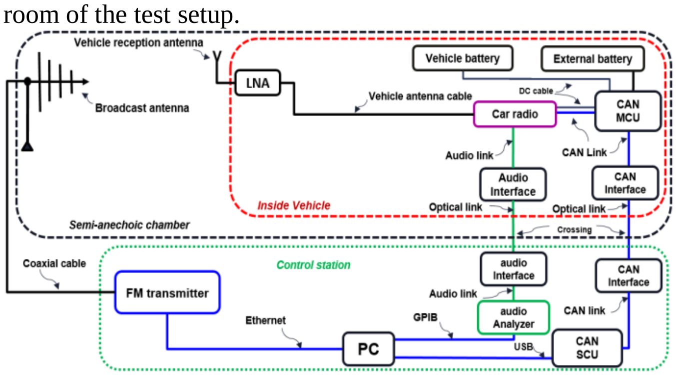

Fig. 5. Complete block diagram of the sensitivity measurement test setup.

The semi-anechoic chamber contains the broadcasting antenna and the VUT. The vehicle is positioned (Fig. 4, 6) so that the vehicle reception antenna coincides with the location of the reception antenna during the calibration test (see section III-B). The transmitting antenna is adjusted to a fixed height h that corresponds to the average height of the vehicles developed by the car manufacturer.

The VUT includes:

- The radio control interface which is composed of a CAN MCU (CAN Master Control Unit) whose role is to send the frequency change commands from the PC (controlling the test setup) to the car radio (via an optical fiber). Also, the CAN MCU allows to switch for vehicle battery to external battery. This allows to perform a sensitivity measurement in the case that the VUT is off (no interference from the vehicle's electrical / electronic components).
- The audio part that contains an audio interface allowing to transmit the sound signal from the audio output of the car radio (via an optical fiber) to the audio analyzer (which is located in the control room).

The MCU and its extra harness were designed according to state-of-the art EMC rules and were validated by CISPR 25 measurements. The results have shown no additional disturbances in the FM band.

The control room contains:

- The laboratory transmitter whose objective is to generate the FM broadcast.
- The audio analyzer whose role is to assess the SNIR by measuring the interference (plus noise) level contained in the baseband signal.
- The CAN SCU (Slave Control Unit) whose role is to transmit (via an optical fiber) the commands from the control PC to the MCU.

Fig. 6. Vehicle in the semi-anechoic chamber under radio test.

The process is the following:

- The carrier frequency must be set to the referred frequency. It is modulated by an internal audio signal whose parameters are adjustable (1 kHz sine wave in our case).
- The car radio must be tuned to the radio station (frequency) to be examined.
- The level of the FM modulated signal is set to a high power level.
- A limit value is defined as the lowest acceptable SNIR for which radio listening is assumed to be acceptable.
- If the measured SNIR (by the audio analyzer) is greater than the acceptable SNIR, the transmitted power is decreased until it reaches the acceptable SNIR.
- The corresponding power at the transmitter antenna is then recorded.
- The sensitivity level S_{EI} is estimated from this recorded power and from the calibration transfer function between transmitting and receiving antennas.
- The sensitivity S_{EI} measurement point corresponds to ($\theta = 90\,°$, $\varphi = 180\,°$) in the spherical coordinate system. The reception threshold S_{EI} (θ, φ) in another direction may be calculated taking into account the gain G_r (θ, φ) of the vehicle antenna in the desired direction.

B. Calibration of the radiated version

A calibration of the transfer function relating the generated field strength to the injected power at the transmitter terminal is necessary. This field magnitude depends on the propagation losses and on the gain of the transmitting antenna, varying with frequency.

The calibration shown in (Fig. 7, 8) enables to retrieve this transfer function. To do so, a given electric power is generated at the transmitting (log-periodic) antenna and the electric field strength is measured using a receiving (biconic) antenna. This calibration is carried out in the semi-anechoic chamber using the configuration illustrated in both Fig. 7 and Fig. 8.

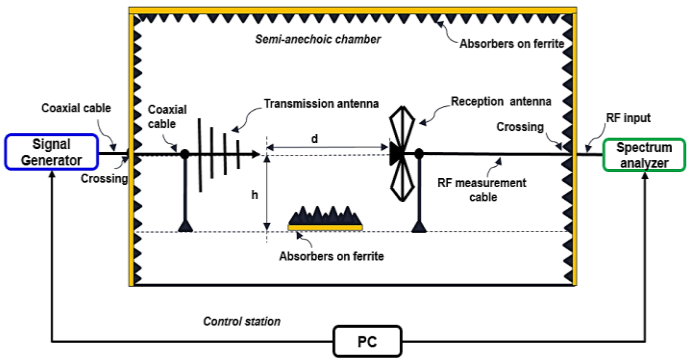

Fig. 7. Illustration of calibration test setup.

The test setup includes a continuous wave signal generator, the broadcasting antenna, a receiving antenna, a spectrum analyzer and a PC to automatically run the test. Due to the specific software used for testing, the calibration procedure requires to set a targeted field or voltage value and consists in adjusting the required power level to reach the targeted value. This is the reason why a generator and a spectrum analyzer are used instead of a VNA. The transmitting antenna and the receiving antenna are placed in line of sight, at the distance *d*, in their respective maximum gain direction and vertically polarized. The antennas are fixed at the height *h* and the distance *d* shall be the one indicated in the calibration antenna factor datasheet of the biconic antenna (e.g. 3 meters).

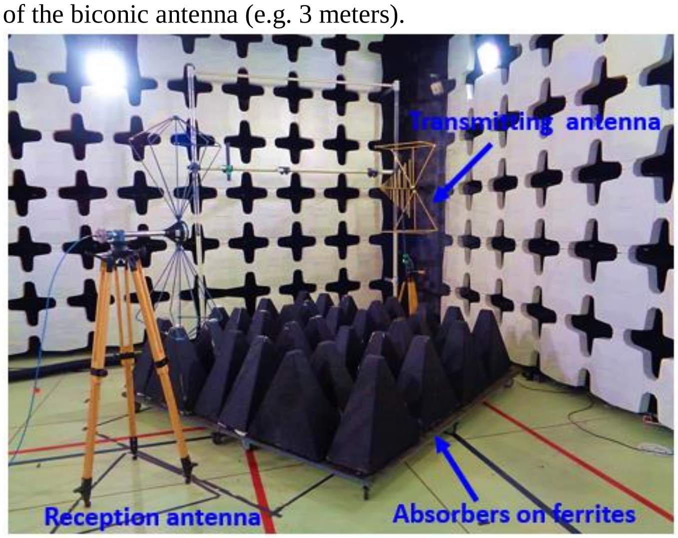

Fig. 8. Photo of the calibration experiment in the semi-anechoic chamber.

An assembly of ferrite and pyramidal absorbing material between the transmitting antenna and the receiving antenna (Fig. 7, 8) attenuates reflections from the metallic floor. This configuration was selected among different arrangements of materials over the floor and was retained since it exhibits the smallest variations of the transfer function according to frequency. Further details are provided in Appendix B.

For each frequency, the transmitted power is then adjusted to reach a prescribed electric field value ($E_{reft} = 80\ dB\mu V/m$) at the receiving antenna location.

We carried out the measurement of the transmitted reference power (P_{reft}) in the configuration consisting in putting ferrite tiles on the ground with pyramidal absorbing material on the top of them. Consequently, the result of the transmission power reading to reach the reference field ($E_{reft} = 80\ dB\mu V/m$) is shown in Fig. 9.

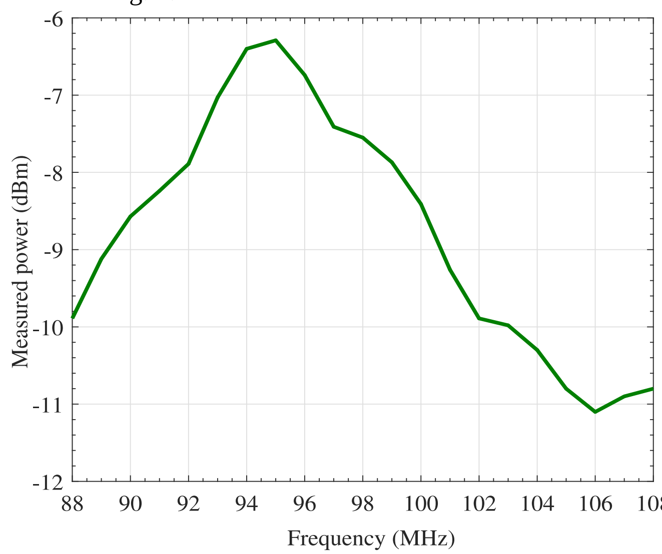

Fig. 9. Measurement of the transmitted reference power (P_{reft}) for a reference field E_{reft}= 80 dBµV/m (assembly of pyramidal absorbing materials and ferrites on the floor) in FM band.

This power varies between a maximum value around -6 dBm at 94 MHz and a minimum value of -11 dBm at 106 MHz. However, the variation of the reference power remains limited to 5 dB over the entire FM band with regard to other configurations (see details in appendix B).

C. Sensitivity threshold (S_{EI}) measurement results

This section presents the sensitivity threshold measurement results in the two operating modes of the VUT:

- Vehicle ON: the vehicle is in normal operation (vehicle engine running).
- Vehicle OFF: the vehicle is completely switched off, only the car radio is operational (using an external 12 V battery).

On the one hand, the sensitivity threshold for the vehicle OFF case gives the variation of the vehicle reception threshold as a function of the intrinsic noise level at the car radio receiver and as a function of the gain of the vehicle antenna. The variation of the latter is further confirmed in the section V of this paper. On the other hand, the sensitivity threshold for the vehicle ON case gives the reception threshold at the car radio receiver according to the additional interference created by on-board components and received by the vehicle antenna.

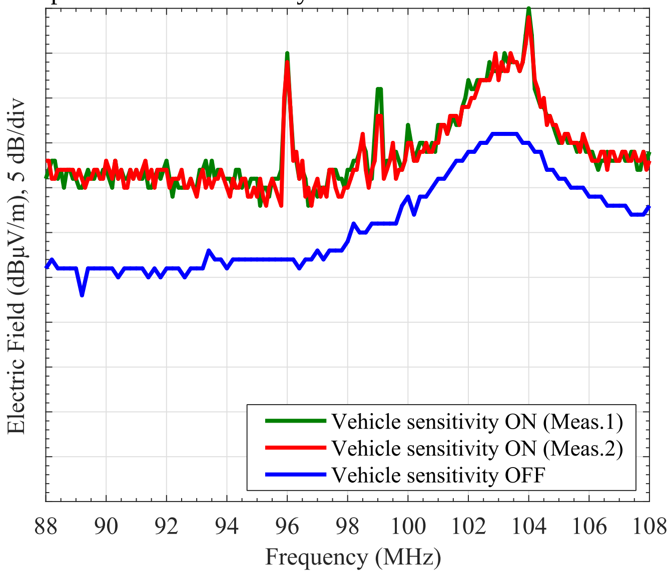

Fig. 10. Representation of three sensitivity measurements S_{EI} in two cases, when the VUT is OFF (car radio receiver ON) and then ON.

Fig. 10 illustrates the superposition of the two threshold measurements S_{EI} (vehicle ON, vehicle OFF) in the FM band. In the vehicle ON case, we notice a strong degradation of the radio receiver sensitivity at 96 MHz, 99 MHz, 100 MHz and 104 MHz. At these frequencies, the steady state interferences generated in the vehicle identified in Fig. 2 are the source of a degradation of radio reception performance.

From 97 MHz to 108 MHz, the threshold S_{EI} (in both ON and OFF cases) reaches higher values. This is the effect of the low gain of the receiving antenna in this frequency range as will be confirmed in section V.

To check for repeatability, we have performed a second sensitivity measurement (Meas. 2 in Fig. 10). The two measurement curves (Meas. 1 and Meas. 2) overlap very well though the interference measurement in PK detection mode (Fig. 3) is not repeatable. This measurement stability is due to the fact that occasional interferences are not very recurrent during the SNIR analysis dwell time (1 second). This is further analyzed in section V.

D. *Advantages and limitations of the radiation mode*

The radiated method has some advantages that can be listed below:

- It allows to qualify the radio reception of a vehicle in case the RF input of the vehicle receiver is not accessible (the tuner and the vehicle antenna are embedded on the same electronic board).
- The coupling of the radio signal and the vehicle interference occurs naturally at the vehicle antenna.
- The vehicle sensitivity threshold measured in radiated mode directly includes the gain (in one direction θ, φ) of the vehicle antenna.
- It enables measuring the sensitivity of the vehicle for different polarizations of the transmitting antenna (vertical polarization, horizontal polarization, 45 °).
- It does not require any modification of the radio reception chain (the antenna of the vehicle remains connected and supplied naturally by the radio).

It should also be noted that this radiated mode version of this test setup has some drawbacks such as:

- It requires a careful electric field calibration prior to the vehicle test (see details in section III-B) for each polarization tested.
- In case the vehicle antenna height is different from the one of the transmitting antenna, the calibration must be carefully correlated according to its radiation pattern.

In order to overcome some drawbacks of the radiated mode, we propose, an alternative version that uses a conductive mode for injecting the FM-modulation signal. This conducting mode is easier to achieve. However, it can only be used if the outputs of vehicle's antennas are accessible.

IV. Adaptation of the Test Setup: Conducted Mode

We mentioned in the previous section that the radiated method is necessary in the case the outputs of the vehicle's antennas are not accessible. Besides, it is not easy to set up because it requires a calibration for each polarization. Regarding the vehicles whose antennas are accessible, we propose in the following a conducted method which is simpler to set up than the radiated method.

This proposed method determines the vehicle reception threshold by conducted injection of a radio signal. It consists in combining the interference and the radio signal by means of a RF combiner and injecting them in the input of the car receiver.

A. *Sensitivity measurement method (at the car receiver input)*

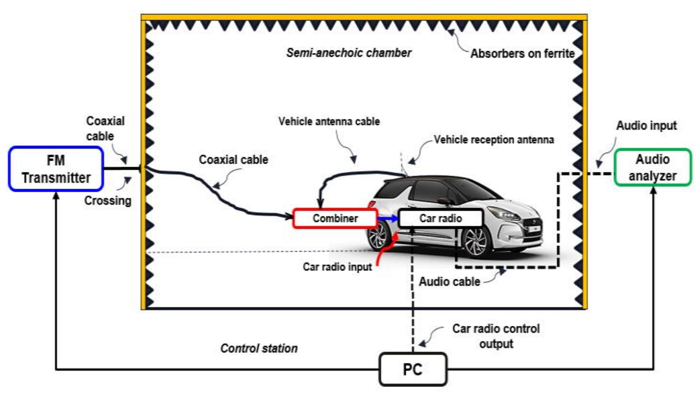

Fig. 11. Test setup of the sensitivity threshold measurement (at the car receiver input) in the semi-anechoic chamber.

The procedure for measuring the sensitivity of the vehicle measured at the input of the receiver (S_A) in the FM band is the same as the one for measuring the S_{EI} threshold (see section III). The combination of the injected radio signal and the interference signal are depicted in Fig. 11 and Fig. 12. Therefore, the quantity S_A measured in this case is a voltage difference and not an electric field magnitude. It consists in determining the minimum voltage measured at the input of the car radio allowing the FM receiver to reproduce correctly the audio signal.

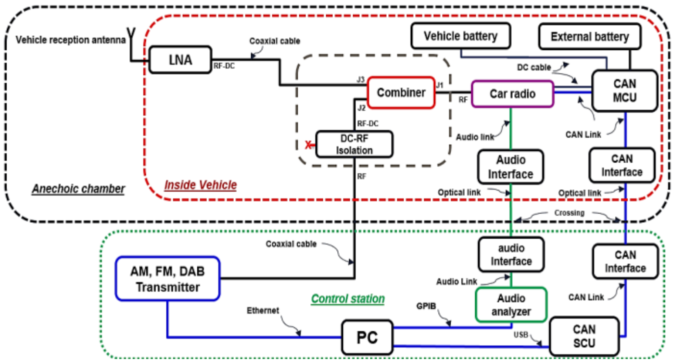

Fig. 12. Complete diagram of the sensitivity measurement (at the car receiver input) test setup.

Fig. 12 shows the overall diagram of the test setup for the conducted mode. The principle of this test is the same as the radiated test (section III). The only difference is the replacement of the antenna with the block delimited by a dotted black line frame at the center of the diagram in Fig. 12.

This block contains:

- A three-way combiner whose role is to associate the interference received by the vehicle antenna (connected to channel J_3 in Fig. 12) and the FM radio signal coming from the radio transmitter (connected to channel J_2 in Fig. 12). At the output of the combiner, the sum of the radio signal and the interference are injected in the RF input of the car radio receiver through the J_1 channel.
- The car radio provides the DC power supply of the low noise amplifier (LNA) of the vehicle antenna through the RF coaxial cable. The insertion of the combiner preventing the car radio to supply the LNA, a DC/RF isolation (placed between channel J_3 and the entry of the LNA) is added to replace the missing power supply.
- A second DC/RF isolation circuit is placed between the input J_2 of the combiner and the RF output of the radio transmitter in order to protect the latter from DC currents (for safety purposes).

The losses of the DC/RF and the combiner are negligible (0.3 dB and 0.5 dB respectively). The photo in Fig. 13 illustrates the installation of the combiner near the car radio receiver (front passenger side).

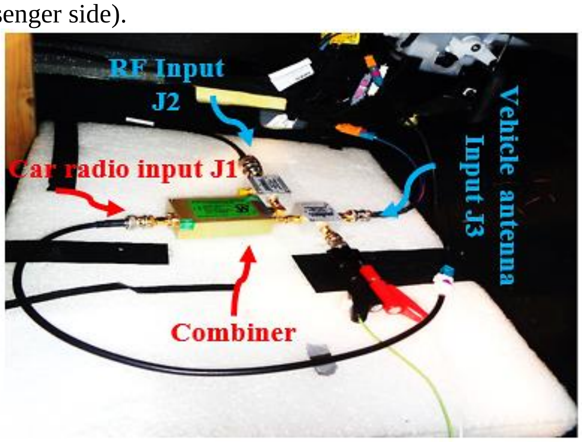

Fig. 13. Installation of the combiner near the car radio receiver (front passenger side).

B. Insertion loss measurement method

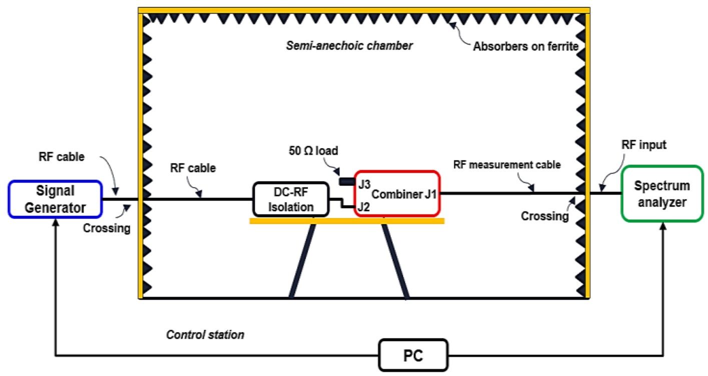

Fig. 14. Illustration of the test setup for measuring the insertion loss of the reception chain.

As already mentioned, the injection of the radio signal in conducted mode requires the introduction of a combiner, an isolation block and coaxial cables between the transmitter and the radio receiver. These elements subsequently introduce insertion losses which have to be taken into account when measuring the reception threshold. Fig. 14 presents the method which consists in measuring (without disconnecting the elements) the insertion losses between the output of the transmitter and the input of the radio receiver. The insertion loss measurement is performed using a signal generator and a spectrum analyzer. The signal generator is connected to the combiner through the DC/RF isolation circuit in the same way as for the RF transmitter (Fig. 12). The spectrum analyzer is then connected to the output of the combiner (J_1). Thereafter, a reference voltage (70 dBµV in our case) must be set. The level of the generator is automatically adjusted until the spectrum analyzer reaches the reference value.

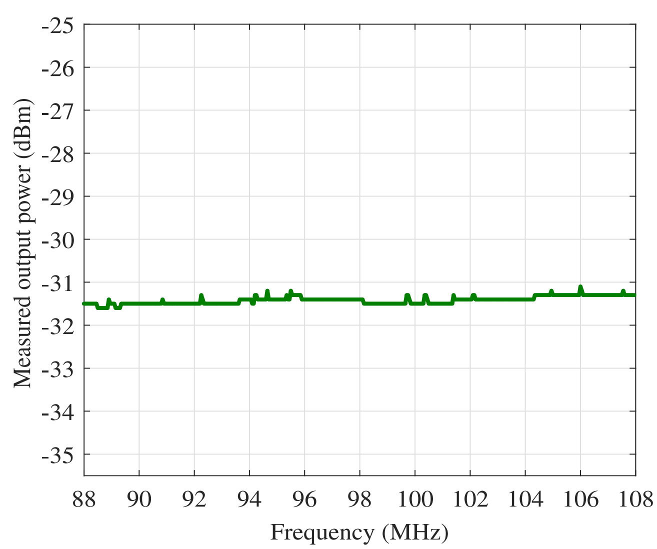

Fig. 15. Power level required at the output of the signal generator to reach the 70 dBµV at the output of the combiner.

Fig. 15 shows the power level required to reach the target (70 dBµV or -37 dBm on a 50 Ω load). Therefore, the average insertion losses of the measurement chain are 5.5 dB.

C. Sensitivity threshold (S_A) measurement results

We provide the measurement results of S_A in the two operating states OFF and ON of the VUT, as previously described.

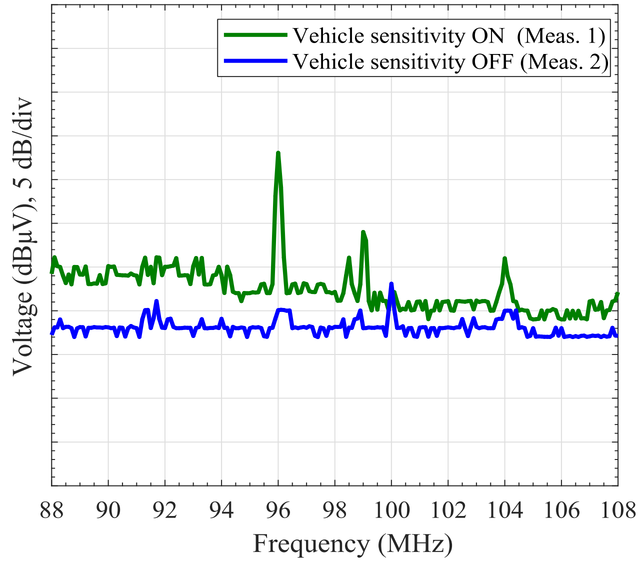

Fig. 16. Representation of two sensitivity measurements S_A in both cases, when the VUT is OFF (car radio ON) and then ON.

Fig. 16 illustrates both the S_A measurements (vehicle ON, vehicle OFF) in the FM band. On the one hand, the measurement with the vehicle OFF is more or less constant over the entire FM band with some fluctuations. This means that the vehicle receiver does not cause significant disturbance to the radio reception (in this case). On the other hand, once the vehicle is turned on, the threshold level increases over the entire band and the sensitivity exhibits a few maximum levels at 96 MHz, 99 MHz and 104 MHz. These three frequencies were also identified in the radiated mode configuration of the test set up. Furthermore, the difference between the two curves is not high except at the frequencies 96 MHz, 99 MHz and 104 MHz, hence, the radio reception quality of this vehicle is quite good since the inference level is close to the intrinsic noise level of the car receiver.

The sensitivity variation remains low in the 97 to 108 MHz frequency range compared to the S_{EI} (radiated measurement, Fig. 10, section III). The transmitted FM signal is directly supplied to the input of the car radio (more precisely to RF input J2 of the combiner). The vehicle's receiving antenna only captures interferences from the vehicle electronic component. Therefore, the fluctuations of the gain of the latter are not visible in this mode.

D. Advantages and limitations of the conducted mode

The strong points of this method are listed below:

- It is simple and quick to set up compared to the radiated test.
- It does not require a calibration test. However, a measurement of the losses of the reception chain is needed.
- The vehicle can be placed in any orientation in the semi-anechoic chamber.

The weak points of this mode may be summarized as follows :

- It requires access to the output of the antennas and to the input of the car radio to insert the combiner.
- The coupling between the interferences and the radio signal is done by means of a combiner and requires to modify the radio reception chain.
- The sensitivity threshold measured in conducted mode does not include the gain of the vehicle antenna (it is necessary to apply post-processing involving the gain of the vehicle antenna).

So far, we have presented two different ways of measuring the modification of the sensitivity level of car radio due to on-board interferences. The following paragraph provides a cross validation between these two methods, demonstrating that they yield very consistent results. It is therefore possible to switch from one to the other by simple post-processing.

V. Cross Validation of Conducted and Radiated Measurements of a Vehicle

We have demonstrated (in section III and IV) that it is possible to measure the vehicle reception threshold in two different ways (radiated mode and conducted mode).
The aim of this section is to demonstrate that qualifying the radio reception by conducted coupling (of RF signal) or radiated coupling (of RF signal) leads to similar results. We here show how to transform the sensitivity threshold S_{EI} (dBµV/m) measured at the vehicle antenna to the sensitivity threshold S_A (dBµV) measured at the input of the car receiver and vice versa.
To do so, we convert the measurement of sensitivity threshold S_{EI} (dBµV/m) obtained in Fig. 10 - Vehicle ON to an equivalent sensitivity threshold $S_{A_{eq}}$ (sensitivity threshold obtained by post-processing expressed in dBµV). This transposed $S_{A_{eq}}$ is then compared to the direct S_A (Fig. 16, vehicle ON). This conversion is based on the result of the calibration (Fig. 9, section IV) and on the measurement of the attenuation (S_{21}) between the transmitter and the input of the car radio receiver. Finally, the $S_{A_{eq}}$ sensitivity threshold is obtained from elementary calculations.

A. Attenuation (S_{21}) measurement test setup

Before determining this equivalent $S_{A_{eq}}$, we first measure the attenuation (S_{21}) between the vehicle antenna and the RF input of the transmitting antenna cable.
Fig. 17 illustrates the setup that allows this measurement.
Furthermore, for the measurement to be performed correctly, a circuit (DC/RF isolation) is required to supply the LNA of the vehicle's FM antenna. Moreover, port 2 of the VNA must be connected to the RF output of this circuit. Also port 1 must be connected to the RF input of the transmitting antenna cable. However, it should be noted that the measurement must be carried out in the same experimental conditions as the sensitivity measurement in radiated mode. In other words, the

vehicle, the antenna, and the absorbers remain in the same position.

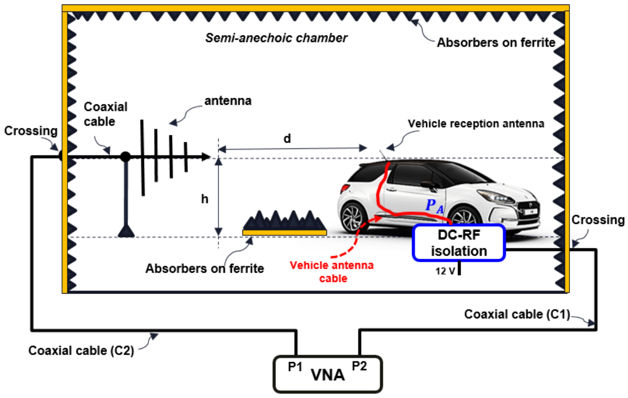

Fig. 17. Illustration of the attenuation (s_{21}) measurement procedure between ports 1 and 2 of the VNA.

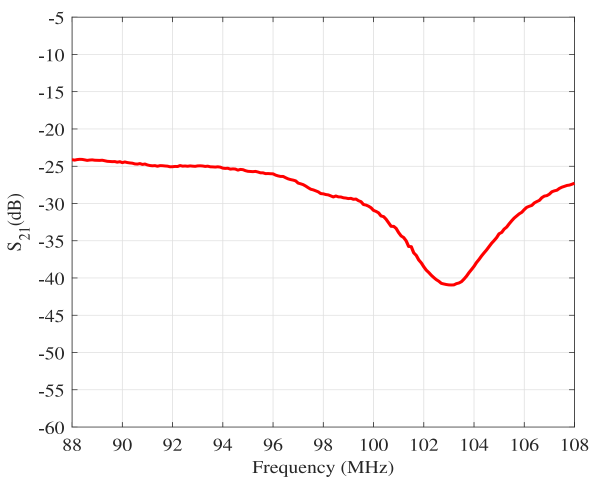

Fig. 18. Result of the attenuation measurement (s_{21}) between port 1 and 2 of the VNA.

Fig. 18 represents the measurement (between port 1 and port 2 of the VNA) of the attenuation in the FM band.
By observing this measurement, we notice that the attenuation fluctuates between -25 dB at 88 MHz and -40 dB at 103 MHz. The coupling drop between 97 MHz and 108 MHz is due to a lower vertical gain of the vehicle's glass antenna in this frequency band and which corresponds to the RF gain measurement results obtained in a near-to-far field test facility. Furthermore, this result is in agreement with the result of the S_{EI} measurement (Fig. 10, section III).

B. $S_{A_{eq}}$ *calculation and comparison with measured* S_A

In this paragraph, we determine mathematically $S_{A_{eq}}$.
Let define p_1 as the output power at the port 1 of the VNA in Fig. 17 and p_2 as the received power at the port 2 of the VNA, when p_1 is supplied to port 1.
In a first approximation considering well matched antennas, we may write:

$$(s_{21})^2 = \frac{p_2}{P_1} \tag{1}$$

We are however interested to calculate the power p_A measured at the input of the car radio receiver. We must then take into account I_{Los} (the insertion loss of DC/RF isolation circuit).

These insertion losses are defined through:

$$(I_{los})^2 = \left(\frac{p_A}{P_2}\right) \tag{2}$$

Furthermore, according to section III, we may write:

$$\left(\frac{p_1}{P_{Reft}}\right) = \left(\frac{S_{EI}}{E_{Ref}}\right)^2 \tag{3}$$

Finally, by combining (1), (2) & (3):

$$p_A = (s_{21})^2 . (I_{los})^2 . (S_{EI})^2 . \frac{P_{Reft}}{(E_{Ref})^2} \tag{4}$$

Since:

$$p_A = \frac{\left(S_{A_{eq}}\right)^2}{50} \tag{5}$$

Finally, in the logarithmic scale we find:

$$S_{A_{eq}}\,(dB\mu\text{V}) = s_{21}(dB) + I_{los}(dB) + S_{EI}(dB\mu\text{V/m}) - E_{Ref}(dB\mu\text{V/m}) + P_{Reft}(dBm) + 107\ (\text{dB}) \tag{6}$$

We have therefore estimated the sensitivity threshold $S_{A_{eq}}$ (dBµV) at the input of the car receiver from the sensitivity threshold S_{EI} (dBµV/m) measured at the level of the vehicle's antenna.

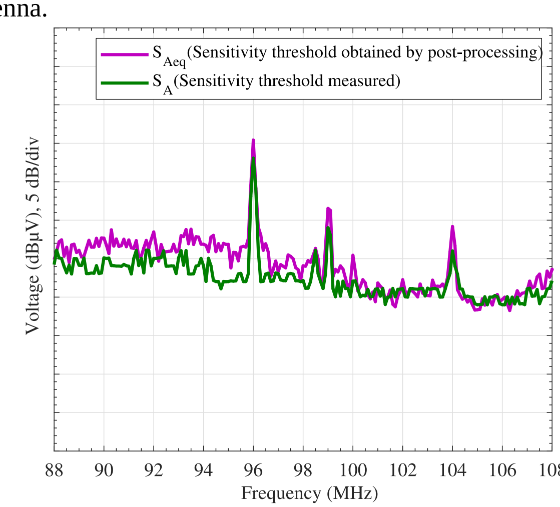

Fig. 19. Comparison between $S_{A_{eq}}$ and S_A, case for vehicle ON.

Using (6), we have calculated $S_{A_{eq}}$ from the sensitivity threshold in radiated mode (S_{EI}) measured in the case of the vehicle ON (Fig. 10, Section III). Fig. 19 shows the comparison between $S_{A_{eq}}$ and S_A (measured in the case of vehicle ON, Fig.16, Section IV). Curves of $S_{A_{eq}}$ and S_A overlap quite well. There is an overall good correlation between curves of $S_{A_{eq}}$ and S_A, the differences are within 3 dB, in particular at 96 MHz, 99 MHz and 104 MHz where the sensitivity reaches the highest values. It may reach 5dB at a few frequencies. This is considered as a very satisfying result regarding noise or interference fluctuations, calibration, measurement uncertainties and systematic errors.

In conclusion, we have shown the possibility to convert radiated mode results to conducted mode results and vice versa by post-processing. Therefore, this provides a cross-validation of our test setup.

VI. Analysis of the sensitivity threshold with regards to CISPR 25 measurements

This section is dedicated to elaborating a comparative analysis between the sensitivity threshold S_A (dBµV) measured at the car radio receiver input and the voltage at antenna terminal obtained by carrying out CISPR 25 measurements.

In a first step, we perform the interference measurements (according to the CISPR 25 standard) and, in a second step, we measure the sensitivity threshold. It should be noted that the interference and sensitivity measurements are performed according to the same experimental conditions, one just after the other.

Fig. 20a presents the interference measured at the input of the car radio in AVG and PK respectively in the case the vehicle is ON. Fig. 20b presents the sensitivity threshold $S_{A_{eq}}$ (dBµV) measured at the input of the car radio in the same case.

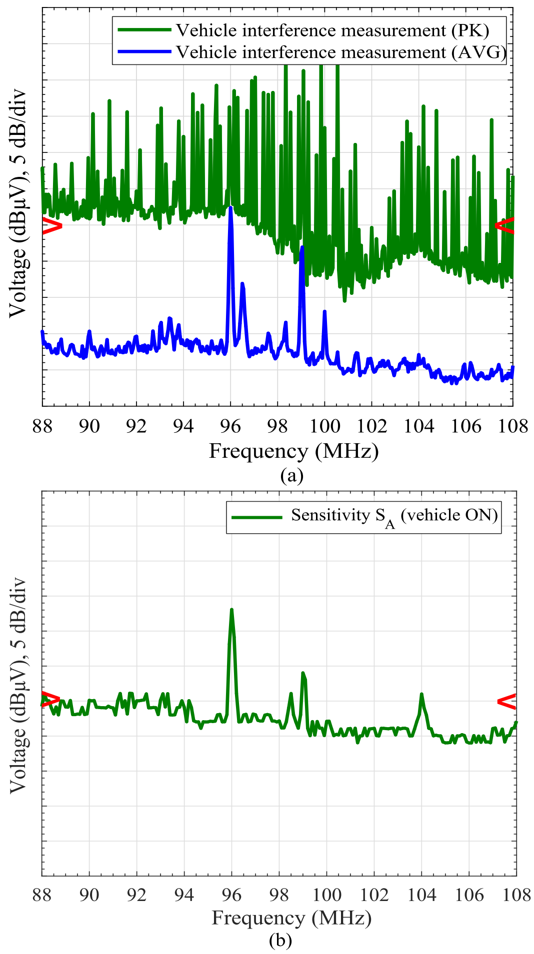

Fig. 20. Comparison between (a) interference measurement and (b) sensitivity measured at the input of the vehicle receiver.

We have added small reference cursors to the figures fig 20a and fig 20b to allow easy comparison between measurements. Note that the average sensitivity level is about 15 dB above AVG interference levels. It is clear that there is no resemblance between the PK measurement in Fig. 20a and the sensitivity threshold spectrum, S_A, plotted in Fig. 20b. Indeed, the associated sensitivity threshold only exhibits local maximum at 96 MHz, 99 MHz, 100 MHz and 104 MHz. On the contrary, S_A threshold is more similar to AVG measurement of Fig. 20a. The measurement of S_A reproduces the local maximum of interference at 96 MHz, 99 MHz and 100 MHz. Thus, it may be more representative to base a risk analysis of quality of reception on the AVG measurement rather than on the PK measurement. However, there are exceptions. For example in our case the AVG measurement could not explain the local maximum of the local sensitivity threshold at 104 MHz.

In conclusion, from the analysis of these results, we may formulate the following hypotheses. First, it is not possible to conclude that the radio reception threshold is correlated with the PK measurement. Secondly, it is not possible to rely solely on the PK and/or AVG measurements to qualify the radio reception by referring to the CISPR 25 standard limits. However, the sensitivity measurement have a much better correlation with the AVG measurements than the PK measurements.

VII. Conclusion

This paper introduced a novel test setup that performs both interference level measurements and assessment of the radio reception performance by measuring the sensitivity threshold of the vehicle receiver. The measurement is carried out in a semi-anechoic chamber. It requires a radio transmitter to create a FM broadcast and an audio analyzer in order to evaluate the signal to interference ratio. The originality of this test setup is the ability to overcome the assessment uncertainties of the limits of the CISPR 25 regarding the evaluation of radio reception.

The proposed test setup has two modes of operation regarding the coupling of the RF transmitting signal: a conducted mode and a radiated mode. The conducted mode allows to determine the sensitivity threshold at the input of the car radio receiver. The conducted mode is very simple to implement and may be used in the case the vehicles antennas outputs are accessible. The radiated mode determines the sensitivity threshold at the vehicle antenna. The main advantage of the radiated version is its aptitude to determine the reception threshold in case the vehicles antennas are accessible. In addition, we have also shown that it is possible to make the link between the conducted mode and the radiated mode by using a simple post-processing.

Experiments have shown that the measurement of interference (in PK or AVG) alone is not sufficient to estimate the radio reception degradation. However, the sensitivity threshold seems to correlate better with the AVG measurement than the PK measurement. Therefore, ultimately, it would maybe be interesting to rely on the AVG measurement rather than PK measurement when applying the CISPR standard. One of the perspectives of the study is to demonstrate the possibility of qualifying the radio reception for digital communication (DAB) by exactly the same methodology.

A. Appendix: how is the acceptable criterion of the listening quality defined?

It should be noted that in this paper we mean by "interference(s)", the interferences of the vehicle components (I) including the noise (N) of the car radio receiver which is part of the vehicle and which cannot be turned off. The acceptable audio interference criterion (C) is based on the interference and noise level contained in the audio signal (after demodulation).

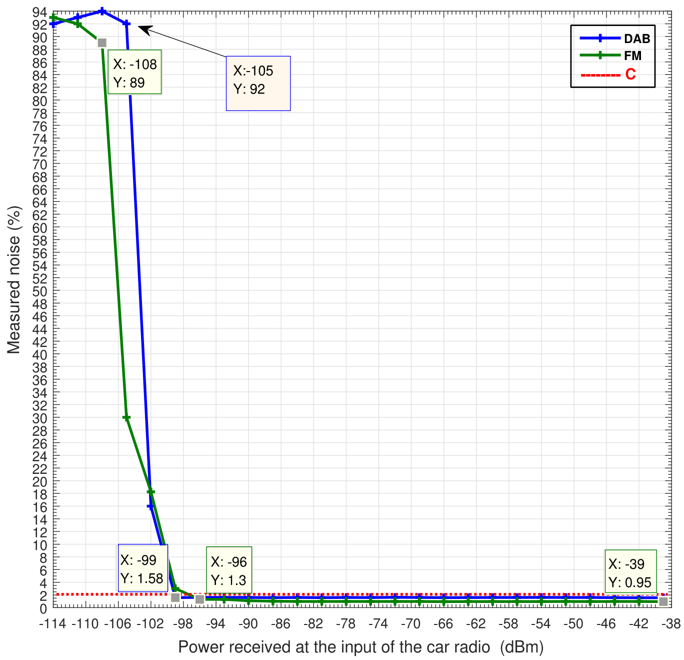

Fig. 21. Curves representing the variation of the noise level at the audio output of the car radio as a function of the injected power at the input of the car radio for FM (at 100 MHz) and DAB (at 174.928 MHz).

Fig. 21 shows that, in the case of the FM band, the power of the noise in the baseband signal changes abruptly when the power received at the input of the car radio increases from around -108 dBm to -96 dBm. For higher input power levels, the percentage of noise varies slightly between 0.95% and 2 %. Fig. 21 also shows a similar behavior in the case of the DAB band. In this case, the noise power in the baseband signal changes sharply as the power received at the input of the car radio increases from around -105 dBm to -99 dBm. Beyond that, the noise power also remains limited between 1.58 % and 2 %. Note that the noise level transition is more abrupt for DAB transmissions, which is probably related to the fact that they are digital signals. From the above, we can therefore consider that the hearing quality is acceptable when the noise power is below the 2 % threshold. This 2 % threshold is therefore used systematically in all our experiments as a decision criterion (good listening / inaudible signal) as a comparison criterion for FM and DAB band.

B. Appendix: Study of the impact of the semi-anechoic chamber's floor in the FM band

The walls of the semi-anechoic chamber (Fig. 8) consist of ferrites covered by pyramidal absorbing material. Only the floor of the chamber is not anechoic (metallic). Therefore, to obtain a small variation of the reference power, it is necessary to attenuate the reflection coming from the floor. Thus, to study the effect of the floor in order to attenuate the reflections, we measured the transfer function (S_{21}) using a VNA between the transmitting antenna and the receiving antenna in the FM band (Fig. 8). These S_{21} parameter measurements are performed in four configurations:

- Floor only (nothing between the antennas).
- Pyramidal absorbing material placed on the floor.
- Ferrite placed on the floor.
- Pyramidal absorbing material and ferrites combined and lay on the floor.

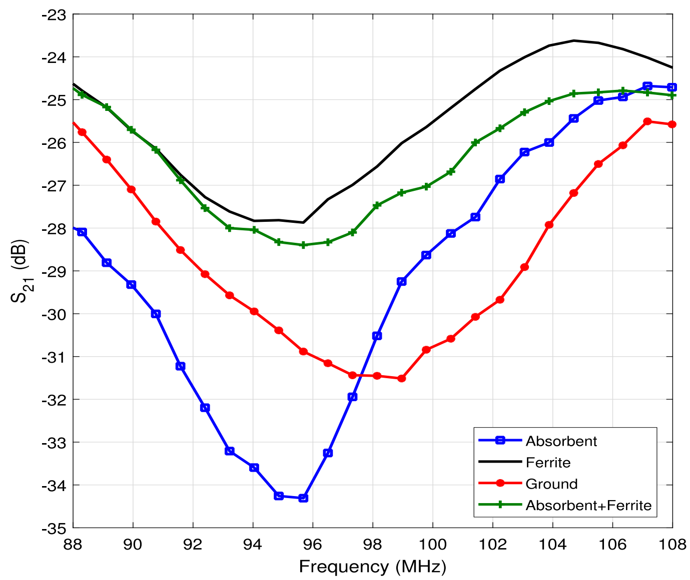

Fig. 22. Comparison between the impact of the different types of floor in FM band.

In Fig. 22, we have plotted the attenuation (S_{21}) for the different configurations. Fig. 22 shows that the attenuation characteristics in the case of pyramidal absorbing materials on ferrite tiles are better, since they do not vary greatly (depending on the frequency) compared to the other configurations. In fact, the minimum value of the S_{21} is -28 dB at the frequency 96 MHz and -25 dB at the frequency 108 MHz, the difference is therefore roughly 3 dB. The case of ferrite tiles alone is also interesting because the variation of the S_{21} is roughly 4 dB. Otherwise, in the situation where the floor is covered with pyramidal absorbing material the attenuation is significant (≈ -34 dB) at the frequency of 96 MHz which is 9 dB below the maximum level (-25 dB) recorded at 108 MHz. Furthermore, in the measurement configuration with metallic floor only, the maximum attenuation is also important (-31.5 dB at 98 MHz) with a maximum variation around 6 dB over the entire FM band. Thus, these measurement results prove that the combination of pyramidal absorbers and ferrite provides the best solution to obtain low variation attenuation in frequency, which involves a reduction of the interference effect associated to the reflection of waves from the floor.

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