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SOPRANOISE

D4.2 Report on the validation of the new quick methods in-situ with recommendations for proper use

April 15, 2022

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1. Introduction

This document is the final report of Work Package 4 (WP4) of the SOPRANOISE project. WP4 has title “Quick & safe methods alongside roads” and is organized in the following tasks:

- **Task 4.1.** Internal review of existing measurement methods that could be good candidates for being quickly applied in situ. Task completed (Milestone M4.1).

- **Task 4.2.** Development and testing in the laboratory of reliable quick methods for in-situ characterization sound absorption and airborne sound insulation of noise barriers. Relying on Task 4.1 and the consortium expertise in developing the EN standard methods, new quick methods have been designed and tested on full-scale laboratory samples. Both the procedure and the equipment are simpler and faster than for EN 1793-5 and EN 1793-6 standards, allowing the use by normal operators after a short training. The same laboratory samples have been tested with the EN methods, in order to assess the degree of correlation of the quick methods with the acknowledged qualification standards. Task completed (Milestone M4.2).

- **Task 4.3.** In-situ validation of the novel quick methods developed in Task 4.2 by comparison with EN 1793-5 and EN 1793-6 methods. This task has been accomplished by UNIBO applying both the new quick methods and the full EN methods on noise barriers installed along the A22 motorway connecting Northern-Italy to Austria. AIT performed laboratory measurements in order to systematically compare the new developed quick methods with the full EN standards. Task completed (Milestone M4.3).

  (*Deliverable D4.2*). The report includes: a summary of the equipment designed for the quick methods; a summary of the proposed measurement procedure; the data measured in Task T4.3 applying both the new quick methods and the full EN methods on noise barriers installed along the A22 motorway (these data are the basis for the validation of the new quick method); the results of the AIT activities performed within Task 4.3. The report will also include some recommendations for proper use of the quick methods.

The present report constitutes the final *Deliverable D4.2* as described above. It is organized as follows: Section 2 outlines the scope of the quick methods; Section 3 recalls the general requirements for the equipment used to apply the quick methods for determining the intrinsic acoustic characteristics of noise barriers (sound absorption and airborne sound insulation); Section 4 presents the measurement procedure implementing the quick methods; Section 5 reports the in-situ tests done by UNIBO along the A22 motorway; Section 6 reports the laboratory tests done with the new measuring equipment at AIT; Section 7 gives some guidelines on the quick methods, including a first proposal for a sampling procedure of the noise barrier under test; Section 8 summarizes the main conclusions.

2. Scope of the quick method

The SOPRANOISE project outlines a 3-steps approach to characterize the intrinsic acoustic characteristics of installed noise barriers (see Figure 1).

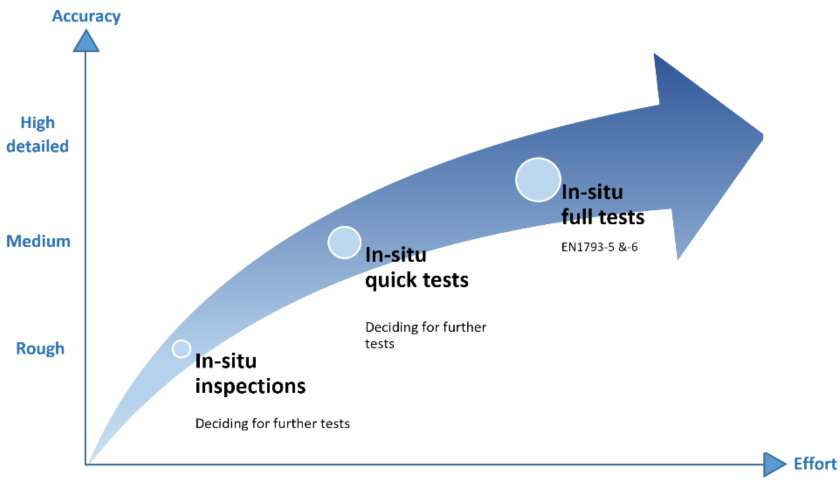


Figure 1. SOPRANOISE progressive 3-steps approach to characterize the intrinsic acoustic characteristics of installed noise barriers.

The quick methods developed in WP4 correspond to the second step of this 3-step approach. As the equipment and the measuring technique is similar for both sound reflection and for airborne sound insulation, from now on, these quick methods will be called, using the singular, “quick method” or “SOPRA method”.

The quick method is a quick **measurement method** for determining the intrinsic characteristics of noise barrier *sound absorption* and *airborne sound insulation* under a direct sound field, i.e., in non-reverberant conditions. The measuring procedure is borrowed with several simplifications from EN 1793-5 and EN 1793-6, which are supposed to be known to the reader [8], [9]. The application procedure is summarized in a compact way in chapter 4, referring to EN 1793-5 and EN 1793-6 whenever possible.
The quick method differs from the visual/aural inspection method used in step 1, because the quick method gives *quantitative* indications, based on *measured* values of the acoustic performance of the noise barrier while the in-situ inspection gives *qualitative* results. Moreover, **an in-situ inspection can spot visible defects but cannot find hidden defects**, e.g. a lack of material inside an acoustic panel; thus, an in-situ inspection can conclude that a noise barrier is *not* acceptable because it has visible defects, but it cannot conclude that a noise barrier is acceptable (for example a lack of material inside a composite panel may be a reason for both a reduced sound absorption and a reduced sound insulation).

The quick method differs from the full EN standards EN 1793-5 and EN 1793-6 used in step 3 because it is designed for quick and easy application, allowing to test many more noise barrier fields in the same time at the price of a reduced accuracy compared to that one of the full EN standards.

The importance of the quick method can be understood considering the two main tasks where acoustic measurements are necessary. If the noise barrier is new, accurate measurements are needed to accept the work. If the noise barrier has been in use for some years, measurements must be used to check whether the acoustic performance of the noise barrier is still acceptable. EN 1793-5 and EN 1793-6 allows to test installed noise barriers where they are, alongside roads, and using a sound field similar to those coming from road traffic, i.e. a direct sound field. Thus, the above tasks could in principle be performed using the EN

standards. However, their application require skilled personnel and a careful operation of the equipment, which limits the amount of tests than can be reasonably done on an installed noise barrier. For example, according to EN 1793-5 the measurements must be repeated displacing the microphone grid few centimetres apart, and in situ on an irregular terrain this means spending a considerable amount of time just to properly place the grid.
The new quick method developed in the frame of the SOPRANOISE project helps road authorities to extend *quantitative* tests to a larger portion of the noise barrier. In fact, a single application of the quick method is easy and quick. Thus, **the quick method can be routinely applied in several locations along the noise barrier**, giving a reasonable estimate of the noise barrier performance, and of the related range of variability over a large sample of noise barrier fields, even if with an uncertainty greater than that one of the full EN standards [10]. Then, when requested and relying on the results of this systematic scan of the noise barrier, some sites where to apply the full EN standards for the final assessment (step 3) could be selected.

Therefore, the quick method is a good substitute of the EN full test when many rapid measurements are need for survey purposes. However, it must be remarked that, **in all situations where legally binding values of the intrinsic characteristics of a noise barrier in a direct sound field - typically expressed as DL_{RI} and DL_{SI} in dB - are required, e.g. to check the compliance of a new noise barrier with the specifications book, the only way to assess them is to use the full EN standards EN 1793-5 and EN 1793-6**, while steps 1 (in-situ inspections) and 2 (quick method) are very useful tools to prepare the selection of the elements / posts to be tested in full.

3. Measuring equipment for the quick method

3.1. UNIBO measuring equipment

The general layout of the equipment designed at UNIBO is shown in Figure 2 [11].

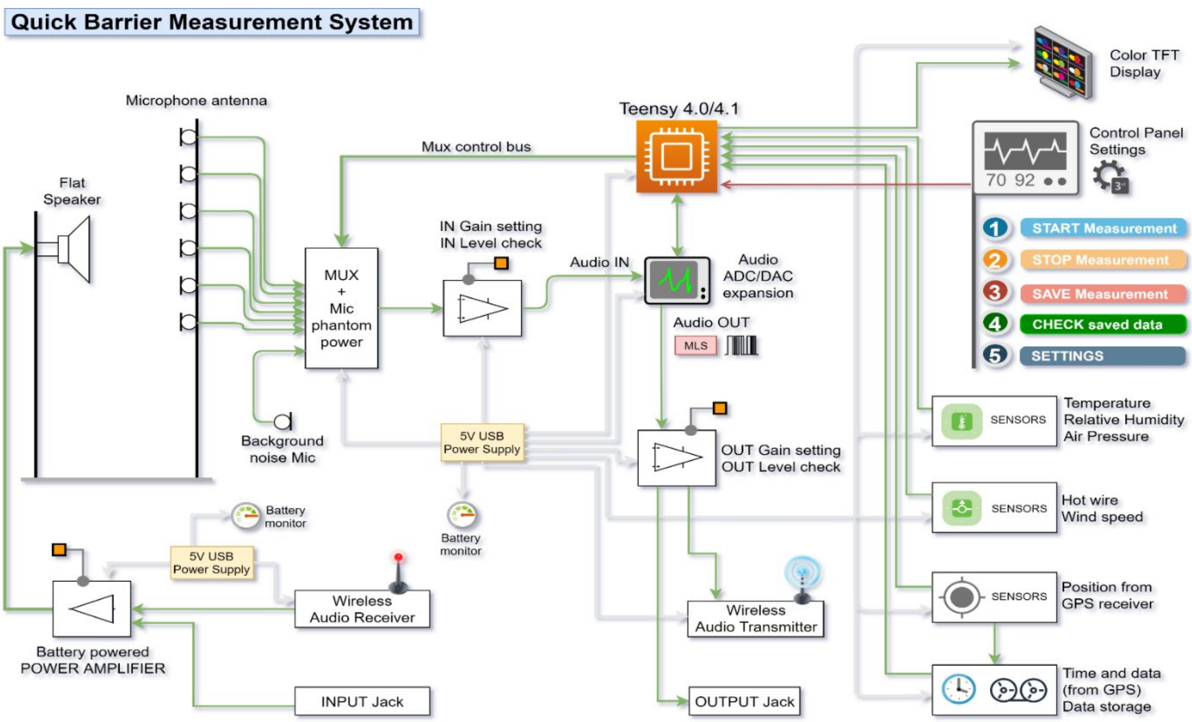


Figure 2. General layout of the equipment designed at UNIBO.

3.1.2. Control and processing unit

The control and processing system is based on a Teensy 4.1 system, including an Arm Cortex-M7 processor, the highest performance member of the energy-efficient Cortex-M processor family. The Cortex-M7 has been designed to deliver a very high level of performance, while maintaining the excellent responsiveness and ease-of-use of the Armv7-M architecture. Its industry leading high-performance and flexible system interfaces are ideal for a wide variety of application areas including automotive, industrial automation, medical devices, high-end audio, image and voice processing, sensor fusion and motor control [1] 89.

Table 1 reports the main technical specifications of Teensy 4.1. More information can be found on the Teensy website: https://www.pjrc.com/store/teensy41.html

It was decided to increase the input dynamics and signal-to-noise ratio through the use of a custom designed external analogue preamplifier with digitally programmable gain (1X, 2X, 4X, 8X, 16X, 32X, 64X, 128X, 256X). A LED is used to check the presence of the input signal.

Figure 3 shows the on-board system Teensy 4.1.

Figure 4 shows its audio adaptor board.

Figure 5 shows the assembled control and processing hardware.

Of course, other systems than Teensy could be used as well. This prototype is just a proof that the control and processing device can be made lightweight.

Table 1: Main technical specifications of the Teensy 4.1 system.

Processor	ARM Cortex-M7 at 600 MHz
RAM	1024K RAM (512K is tightly coupled)
Flash memory	2048K Flash (64K reserved for recovery & EEPROM emulation)
USB ports	2 USB ports, both 480 Mbit/sec
CAN Bus	3 CAN Bus (1 with CAN FD)
I2S ports	2 I2S Digital Audio
S/PDIF ports	1 S/PDIF Digital Audio
SD	1 SDIO (4 bit) native SD
SPI	3 SPI, all with 16-word FIFO
I2C	3 I2C, all with 4-byte FIFO
Serial I/O	7 Serial, all with 4-byte FIFO
DMA channels	32 general purpose DMA channels
PWM pins	31 PWM pins
Digital pins	40 digital pins, all interrupt capable
Cryptographic Acceleration	yes
Random Number Generator	yes
RTC for date/time	yes
Programmable FlexIO	yes
Pixel Processing Pipeline	yes
Peripheral cross triggering	yes
Power On/Off management	yes

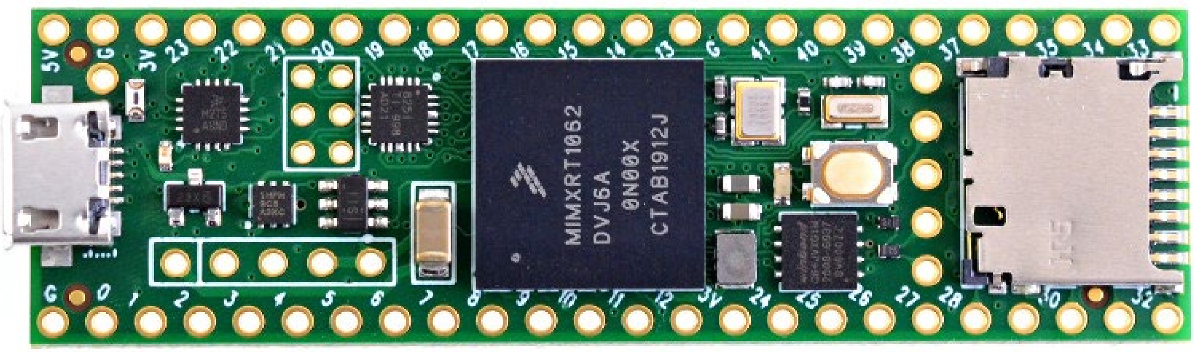


Figure 3. The on-board system Teensy 4.1.

Figure 4. The audio adaptor board for Teensy 4.1.

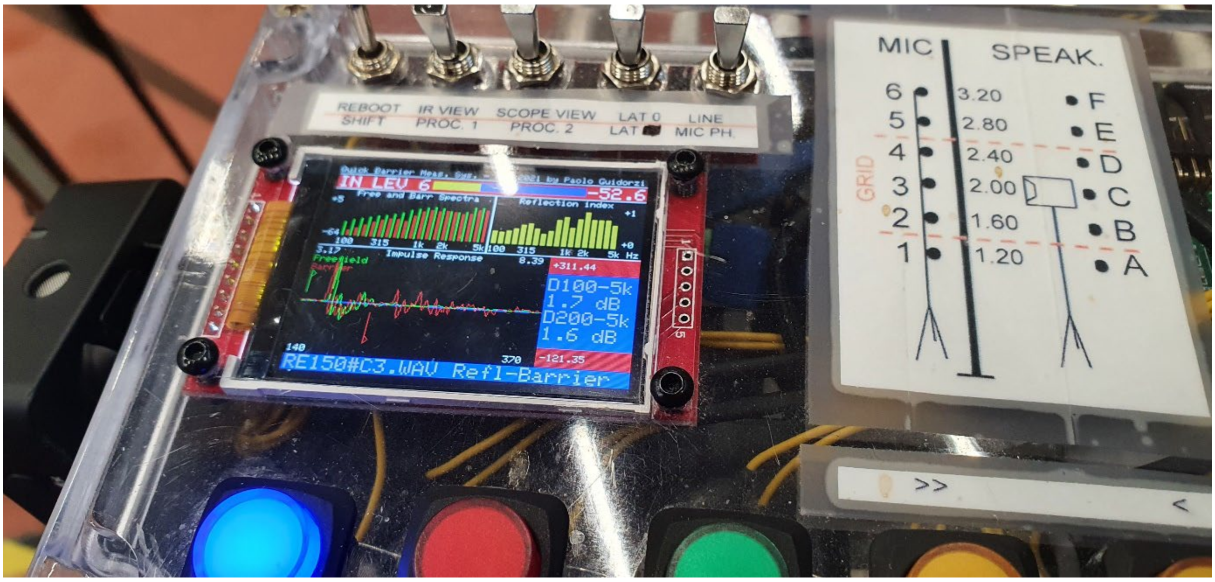


Figure 5. The assembled control and processing hardware.

3.1.3. Microphones

As input sensors, robust and inexpensive electret microphones CMA-4544PF-W have been selected (see Figure 6). They are delivered worldwide by AZ Delivery with the code *5 x GY-MAX4466 Electret Microphone with amplifier* (open circuit sensitivity -44 ±2 dB frequency response 20-20000 Hz, typical S/N 60 dB(A)) [2] .

The electret microphone is connected to the LINE IN (not MIC IN) input of the Teensy external soundcard chip SGTL5000 without any other circuit or pre-amplifier, except the multiplexer, that act simply as an ON/OFF switch, to select one of the 6 microphones. The ADC has 85 dB S/N, -73 dB THD+N. The internal digital preamp inside SGTL5000 is kept at unity gain. The phantom power supply (3.3 V) is given to the electret capsule by means of a 2.2 kΩ resistor, switchable ON or OFF in case other kind of microphones are used. A decoupling capacitor is inserted to eliminate DC voltage.

The input and output analogue gains are fixed (no different settings allowed), in order to avoid measurement errors due to gain changes during the measurement session.

Figure 7 shows the magnitude of the frequency response of an electret microphone compared with that of a PCB microphone adopted for the EN 1793 square array (The curve of the electret microphone has been shifted upward by 11 dB for a better readability). As can be seen, they are nearly identical in the relevant frequency range (100-5000 Hz in one-third octave bands).

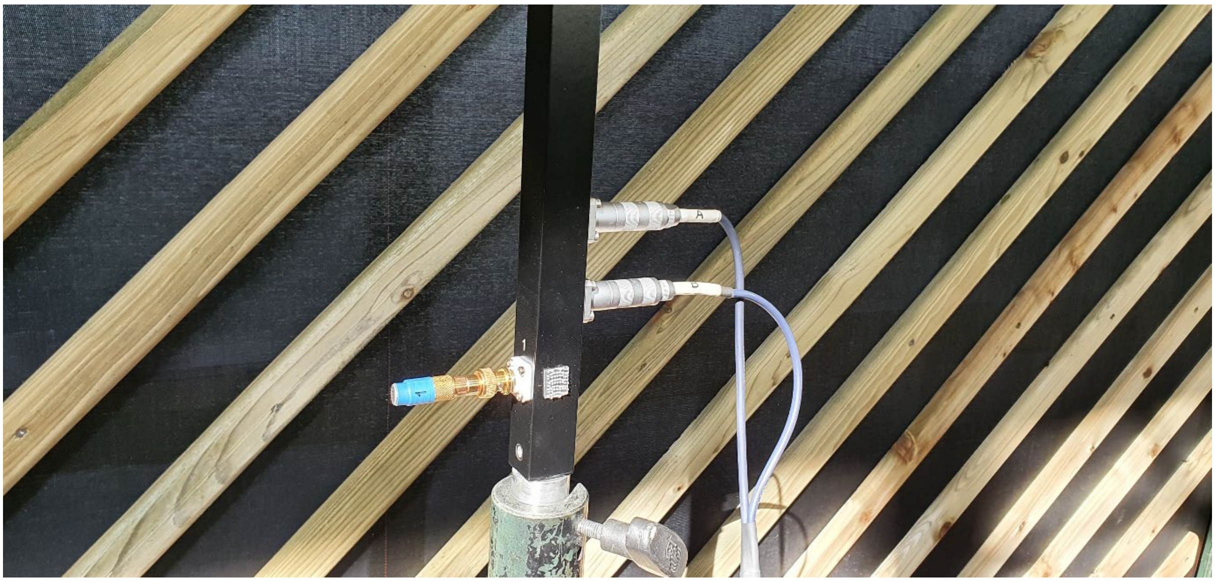


Figure 6. One out of six electret microphone mounted on a vertical aluminium stick.

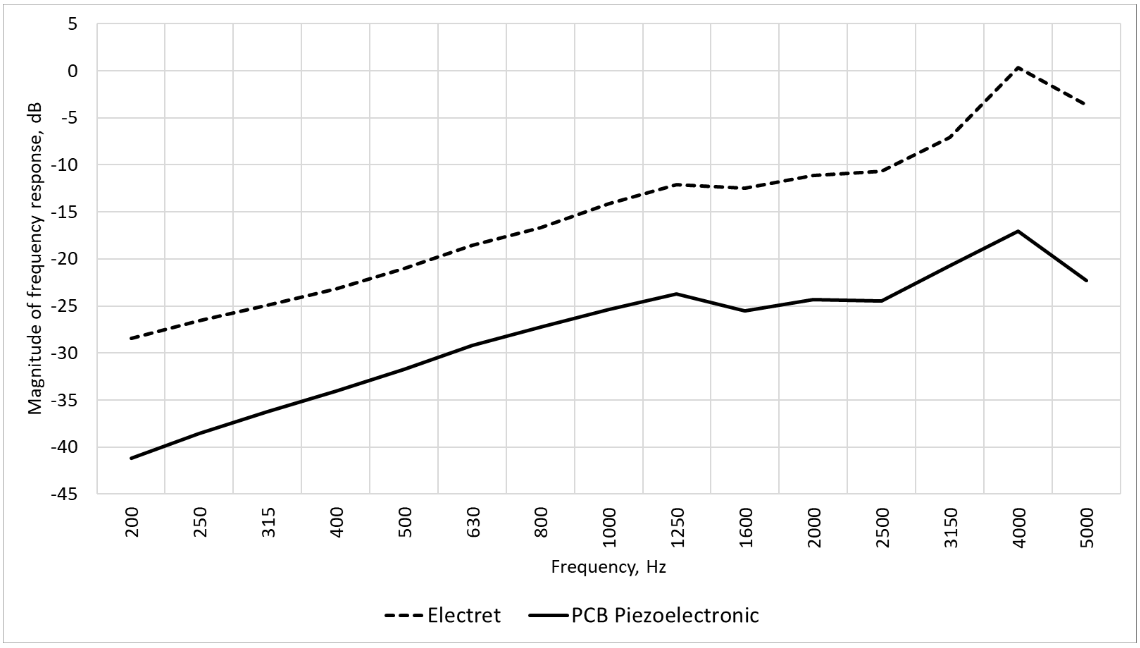


Figure 7. The magnitude of the frequency response of an electret microphone compared with that of a PCB microphone adopted for the EN 1793 square array in the interesting frequency range for this kind of measurements. The Y-axis is in dB with an arbitrary reference. The curve of the electret microphone has been shifted upward by 11 dB for a better readability.

As there is no analog pre-amplifier, it is not possible to have a figure for the conventional dynamic range of microphone + pre-amplifier alone. The S/N of the microphone and the connected measurement chain should be considered instead.

The SGL5000 chip ADCs and DACs work internally at 24 bits, while audio data in current Teensy version are exchanged with 16-bit resolution. This allows approximately a nominal S/N equal to 96 dB on signal input and output.

Loopback measurements on the quick system (signal output connected directly to signal input with a cable), have been done in order to measure the performance of the quick system audio chain without microphone and loudspeaker (DAC → output → input → ADC). A long MLS signal have been used to get the impulse response (see Figure 8). The results are:

- RMS power of time data measured far away from the peak of the impulse response ("internal noise"): -5,57 dB;
- RMS power of time data measured around the loopback impulse response ("signal"): 76,79 dB.

Then an effective dynamic range of 82,4 dB can be estimated: 76,8 – (-5,6) = 82,4 dB.

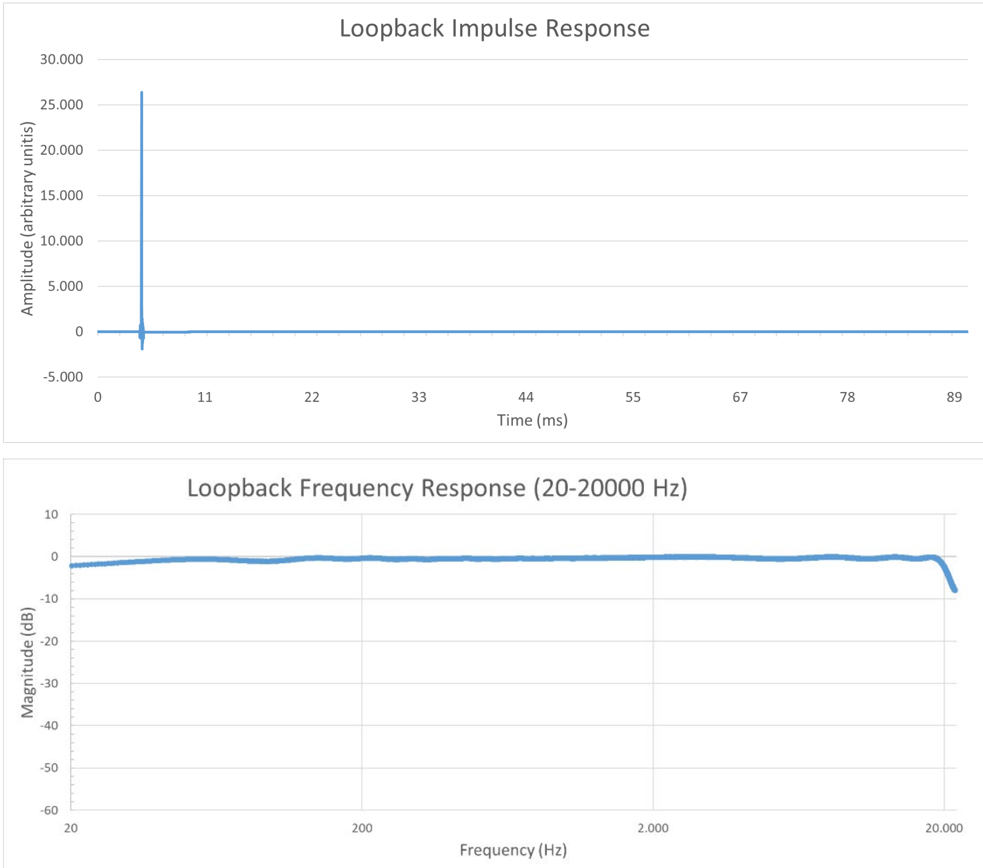


Figure 8. Loopback impulse response (top) and narrow band frequency response (bottom) of the newly developed quick system.

Apart these considerations, the goal here is to get results with the newly developed quick system close to those from the standard equipment complying to EN 1793-5 and EN 1793-6. The measurements shown in report D4.1 proof that this is the case.

The electret microphones are mounted on a lightweight aluminium stick, made from two pieces connected by a hinge that can be easily folded and transported in a car. When mounted, it supports six microphones on a vertical line, covering the whole height of a noise barrier 4 m high (Figure 9). It is important to point out from now on that *not all of the 6* microphones are essential for the quick method: the 3 central microphones suffice in most common cases, but the other 3 (one below and two above the 3 central ones) allow quick tests of the full capabilities of the method in unusual spots on the noise barrier without the need to move or adapt the linear antenna. These possibilities will be illustrated in the following.

Figure 9. The linear microphone antenna on a supporting stand. The microphones are labelled “M1” to “M6” from the bottom to the top. On a flat ground, M1 is at 1,20 m from the ground. The spacing between subsequent microphones is 0,40 m.

3.1.4. Loudspeaker

For the acoustic signal output, a lightweight loudspeaker is enough, as noise rejecting test signals, like ESS and MLS, are used in SOPRA measurements. UNIBO built a lightweight loudspeaker cabinet where many broadband drivers can be placed (Figure 10). The main data for two of them are shown in Table 2. More data on the B&C driver are shown in report D4.1 and on the B&C website [3] .

Table 2: Main technical specifications of the 6NDL38 LF driver by B&C Speakers and on the SICA Z002601 driver, as declared by the manufacturers.

Manufacturer	B&C Speakers 6NDL38 LF (Italy)	SICA Z002601 (Italy)
Nominal Diameter	170 mm (6,5”)	129 mm (5”)
Nominal Impedance	8 Ω	8 Ω
Minimum Impedance	6,0 Ω	6,0 Ω
Nominal Power Handling	150 W	60 W
Continuous Power Handling	300 W	120 W
Sensitivity	92,0 dB	91,1 dB
Frequency Range	70 - 6000 Hz	125-5000 Hz
Voice Coil Diameter	38 mm (1,5“)	32 mm (1,25“)
Winding Material	Copper	Copper
Former Material	Kapton	Epotex
Winding Depth	12,0 mm (0,5“)	9 mm 0,35“)
Magnetic Gap Depth	6,0 mm (0,25“)	6,0 mm (0,25“)
Flux Density	1,15 T	1,10 T

Figure 10. The lightweight loudspeaker used at UNIBO for SOPRA measurements.

Figure 11 compares the frequency response of the lightweight loudspeaker and of a common loudspeaker used in Europe for EN 1793-5 and -6 measurements: the Zircon© loudspeaker by Acoustic Engineering. As a further improvement, a wireless transmitter/receiver, was tested for wireless transmission of the input signal to the loudspeaker. As can be seen, it introduces no bias or distortion.

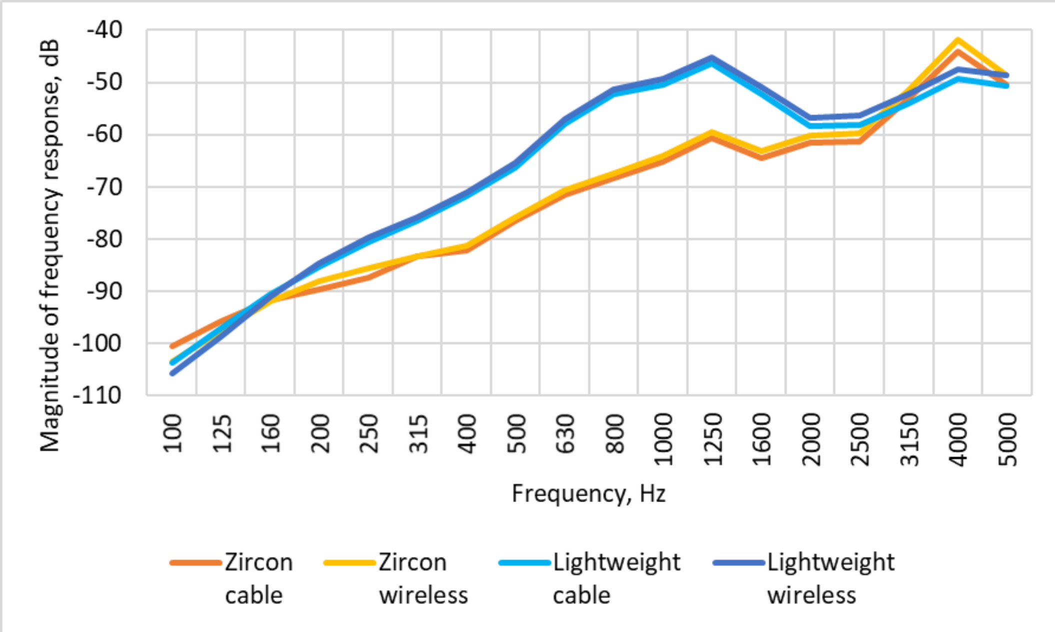


Figure 11. Magnitude of the frequency response of the UNIBO lightweight loudspeaker and the Zircon© loudspeaker, with and without wireless transmission.

Figure 11 shows that the magnitude of the frequency response of the lightweight loudspeaker is greater or equal to that of the Zircon© loudspeaker from the 160 Hz to the 2500 Hz one-third octave bands. Figure 11 also shows that the wireless system does not alter the magnitude of the frequency response of the loudspeaker. Thus, the heavier Zircon© loudspeaker can be replaced by the lighter one, portable by one operator and connected through a wireless system, without affecting the results.

Figure 12 shows the impulse response of the lightweight loudspeaker overlapped by a 3 ms window; Figure 13 shows the impulse response of the Zircon© loudspeaker overlapped by a 3 ms window. It can be seen that they have more or less the same length, even if the Zircon impulse response is more ringing.

Finally, Figure 14 shows the wireless transmitter/receiver system, circled in red, connected to the UNIBO lab-made lightweight loudspeaker (left) and to the control and processing system.

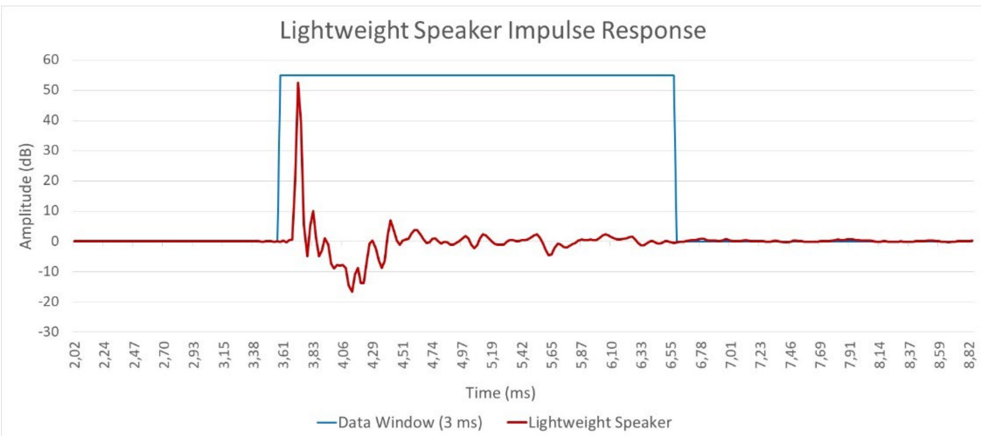


Figure 12. Impulse response of the lightweight loudspeaker framed by a 3 ms window.

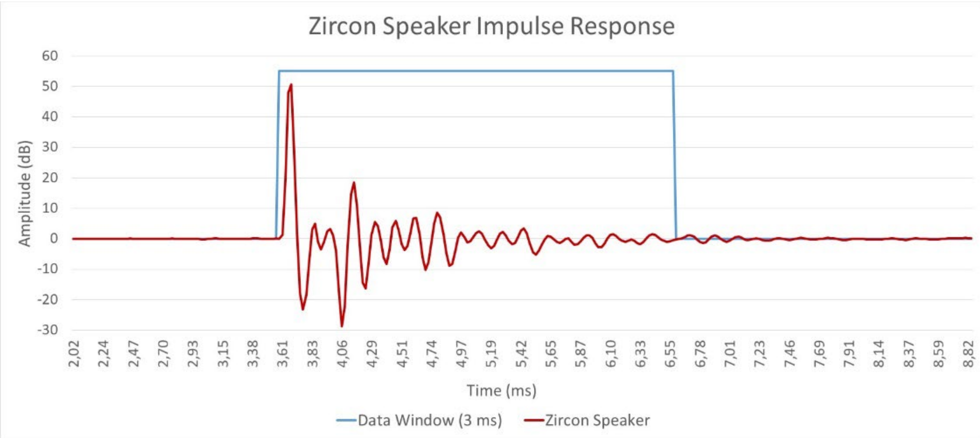


Figure 13. Impulse response of the Zircon© loudspeaker framed by a 3 ms window.

Figure 14. Wireless transmitter/receiver system, circled in red, connected to the UNIBO lab-made lightweight loudspeaker (left) and to the control and processing system (right).

3.2. AIT measuring equipment

AIT develops acoustic measurement systems for many projects. Figure 15 shows the general layout of the quick measurement system used in the frame of the SOPRANOISE project.

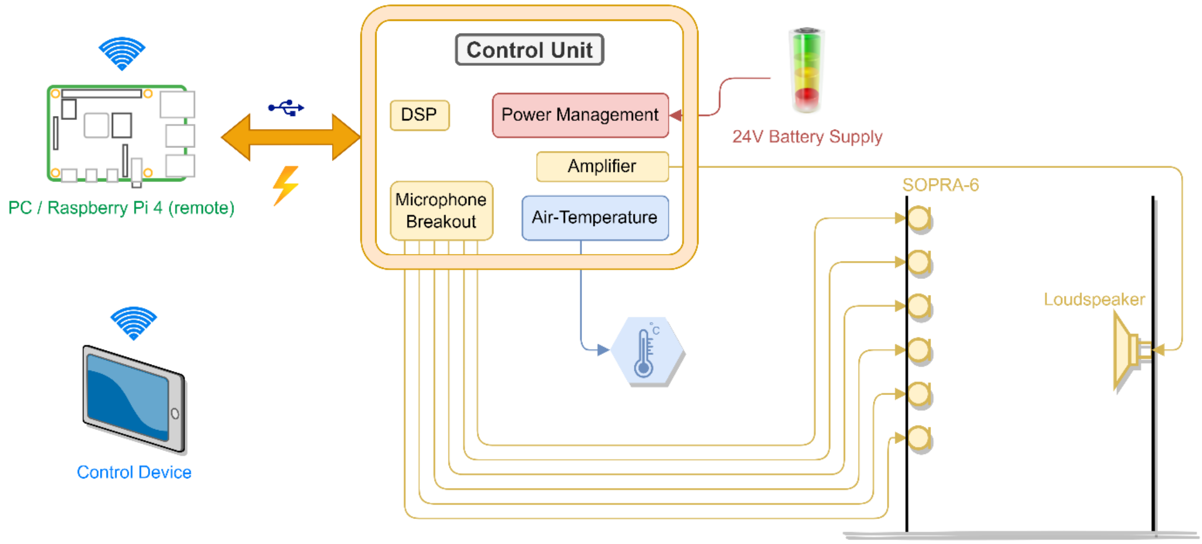


Figure 15. General layout of the equipment used by AIT.

3.2.2. Control and processing unit

The system has a separate control and processing unit. As processing unit any general-purpose computer can be used (based on any modern x86 or x64 CPU) as the control unit is connected and accessed via USB, which is the most common connection type for peripheral devices. In Figure 15 as processing unit a Raspberry Pi 4 is shown; it is powered by the control units power management.

The Raspberry Pi is probably the most used low-cost computer with an extensive community providing new software and support. The Raspberry Pi 4 Model B uses a 64-bit quad core Cortex-A72 processor at 1.5 GHz which can run a full operating system. This gives access to high-level programming languages and fulfils AIT's strategy of inter-operability of the measurement systems.

Table 1 shows the main specification details of the Raspberry Pi 4 [4] , which has more than enough computing power for the given task. Figure 16 shows an image of the Raspberry Pi 4. As "system on a chip" (SOC) the Raspberry Pi 4 only needs a form factor of 8.5 cm x 5 cm x 2 cm with a weight of approximately 42 g to be a runnable system.

Table 3: Main technical specifications of the Raspberry Pi 4.

Processor	Broadcom BCM2711, Quad core Cortex-A72 (ARM v8) - 64-bit SoC @ 1.5 GHz
RAM	2GB, 4GB or 8GB LPDDR4-3200 SDRAM (depending on model
Flash memory	Micro-SD Card Slot (typically 32 GB to 512 GB)
USB ports	2 USB 3.0 ports, 2 USB 2.0 ports
GPIO	Raspberry Pi standard 40 pin GPIO header (I2C, PWM, 4x SPI, I2S, Serial)
Video	2 × micro-HDMI ports (up to 4kp60 supported)

	2-lane MIPI DSI display port
Camera	2-lane MIPI CSI camera port
Graphics	H.265 (4kp60 decode), H264 (1080p60 decode, 1080p30 encode) OpenGL ES 3.1, Vulkan 1.0
Power Supply	5V DC via USB-C connector (minimum 3A*) 5V DC via GPIO header (minimum 3A*)

Due to the small size of the Raspberry Pi 4, it is possible to include it with the control unit into a box mounted at the base of the microphone standing and connect the Raspberry Pi 4 via a remote connection from a laptop or tablet (as shown in Figure 15).

This reduces cable length and gives the operator the possibility to move freely, which is an important factor for measuring noise barriers on narrow service lanes. Nevertheless, for inter-operability also a standard laptop can connect to the control unit.

The control unit is a custom printed-circuit board (PCB) designed by AIT; it is shown in Figure 17. Its main purpose is to control and connect the different components necessary for the measurement. The main components are:

- Digital signal processor (DSP) board providing synchronous 24 input and 24 output audio Channels via USB (Class Compliant Audio) at 48 kHz with 24-bit resolution
- Texas Instruments TAS6421-Q1 digital audio power amplifier chip (single-channel, 75 Watt) [5]
- Arduino MKRZero microcontroller
- A microphone breakout section for connecting the digital microphones
- A low-cost air-temperature sensor
- DC-DC converters for using a battery pack as power source for all components on the board as well a sufficiently strong 5V power supply for the processing unit (e.g. Raspberry Pi 4).

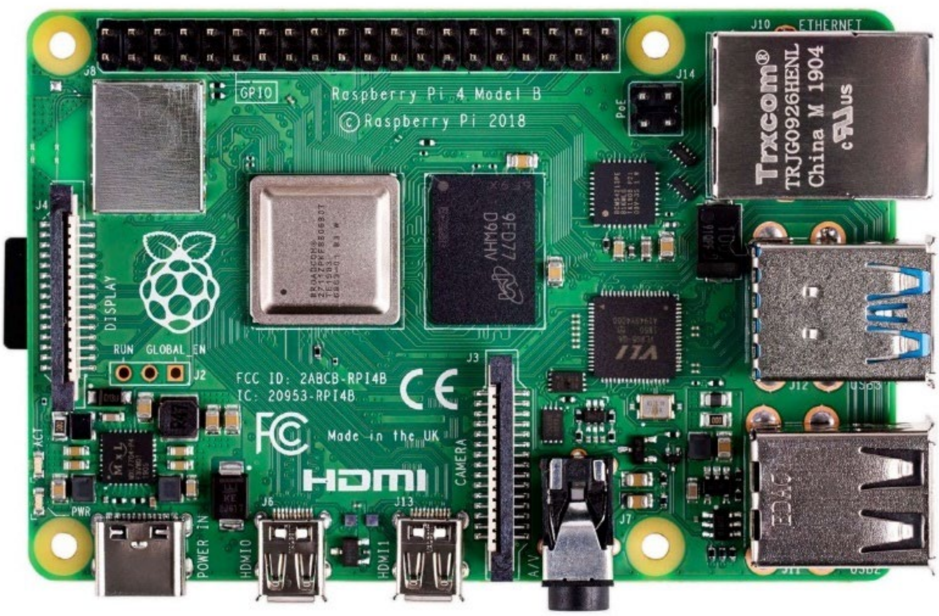


Figure 16. Raspberry Pi 4 processing unit.

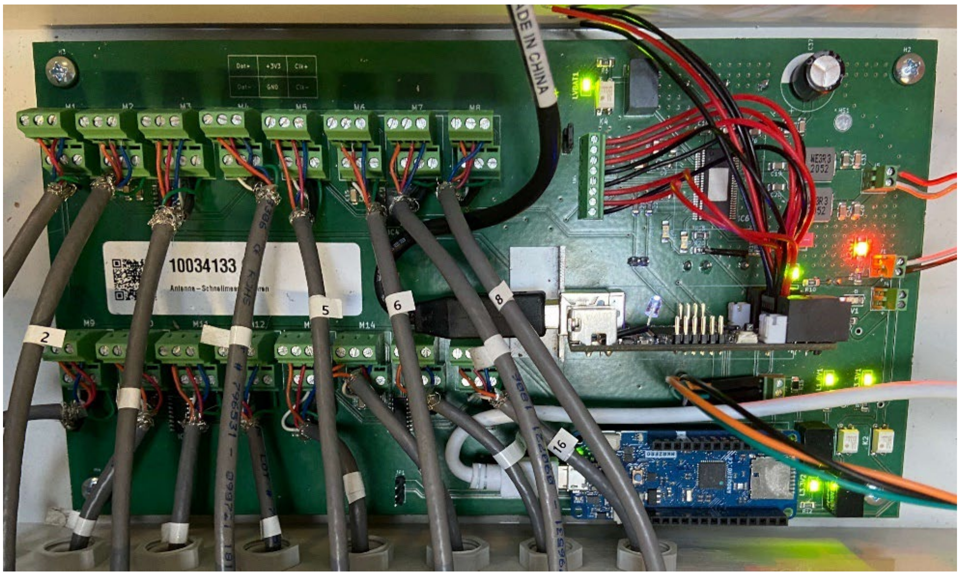


Figure 17. Control unit printed-circuit board developed at AIT with: power amplifier (upper right corner), DSP board (vertical mounted, right centre), microcontroller (lower right) and microphone breakout (left).

As the system is a general purpose one, not especially designed for this project, it is built for recording 16 microphone channels at the same time. Due to the small form factor in comparison to a tripod stable enough to support the microphones till several meters in height, it was not necessary to design a reduced board for the prototype of this project.

3.2.3. Microphones

For a new measurement system AIT focuses on digital MEMS-microphones as acoustic transducers, which are commonly used in smartphones, laptop computers or portable music recorders. Many current MEMS microphones fulfil the necessary requirements for the quick measurement system; however, due to the high availability during the present chip shortage, the microphone SPG08P4HM4H-1 by Knowles Electronics LLC [6] was selected.

Figure 18 shows the typical free-field magnitude and phase response, which shows a flat frequency response (< 3 dB) from 30 Hz to 10 kHz, an acoustic overload point of 120 dB (0 dBFS) and a signal-to-noise ratio (SNR) of 64 dB(A) at 94 dB SPL @ 1 kHz. With a noise floor power spectral density below -110 dB (FS(A)/Hz) in the relevant frequency range, noise is not a problem of the microphone chip with a form factor of 4 mm x 2 mm x 1,1 mm. Due to the direct digital output of the microphones and a signal acquisition with 24 bit resolution, these specifications are valid for the whole acquisition process.

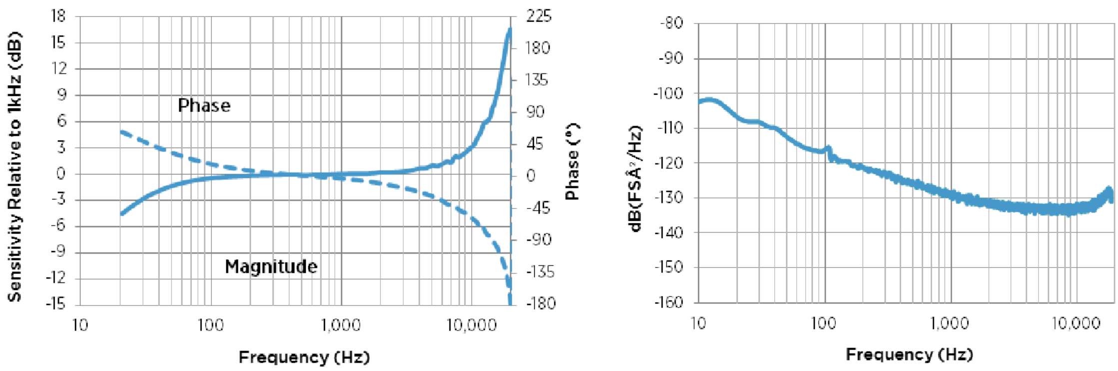


Figure 18. Typical free-field magnitude and phase response (left) and noise floor power spectral density (right) for the SPG08P4HM4H-1 MEMS microphone [6] .

Figure 19. Side (left) and top (right) view of the microphones. In the right picture the golden microphone chip with its open top port is visible.

The microphones are soldered on a mini-PCB and mounted in a 3D printed housing, which was previously designed at AIT for outdoor measurements, as its outside diameter is compatible with windscreens and calibrators for professional ½" microphones. The microphone mounted on the PCB in its housing is shown in Figure 19.

Figure 20 shows the linear microphone antenna used for the measurements in the AIT laboratory in Vienna. For the scope of this research only 6 of the 16 microphones have been used: these are labelled "M1" to "M6" from bottom to op, according to the setup used in the UNIBO measurements.

Figure 20. The linear microphone antenna used for the measurements on a supporting stand in the AIT laboratory in Vienna. For the scope of this research only 6 microphones labelled “M1” to “M6” from bottom to top have been used, according to the setup used in the UNIBO measurements.

3.2.4. Loudspeaker

As Loudspeaker a PAB-305/SW [7] by img Stageline was used, which is a 5” full range speaker in a compact bass-reflex system. Although, the bass-reflex system is not fully in accordance with the EN 1793 package, the small form factor and low weight in comparison to its high-power handling capabilities make the loudspeaker a valid choice for the quick measurement procedure. Table 4 gives an overview of the technical specification of the loudspeaker.

Table 4: Main Specification details of the img Stageline PAB-305 loudspeaker.

Manufacturer & Type	Img Stageline PAB-305/SW
Diameter	13cm (5”)
Nominal Impedance	8 Ω
Nominal Power Handling	100 W
Continuous Power Handling	200 W
Sensitivity (1 W/1m)	93 dB
Frequency Range	140 Hz – 18 kHz
Max. rated SPL	109 dB
Weight	1,2 kg

Figure 21 shows the (normalized) impulse responses of AIT’s standard measurement equipment for measurements according to EN 1793-5 or EN 1793-6 with an Avantone MixCube Active and Brüel&Kjaer LAN-XI digital acquisition units with Brüel&Kjaer 4189 microphones (left) and the quick measurement system described above with an img Stageline PAB-305 speaker as described above (right). As the loudspeakers have the strongest influence on the impulse response of the whole sound source, the description is shortened to the loudspeaker name. Both loudspeakers have the relevant energy in a 3 ms window, although the MixCube Active seems more ringing.

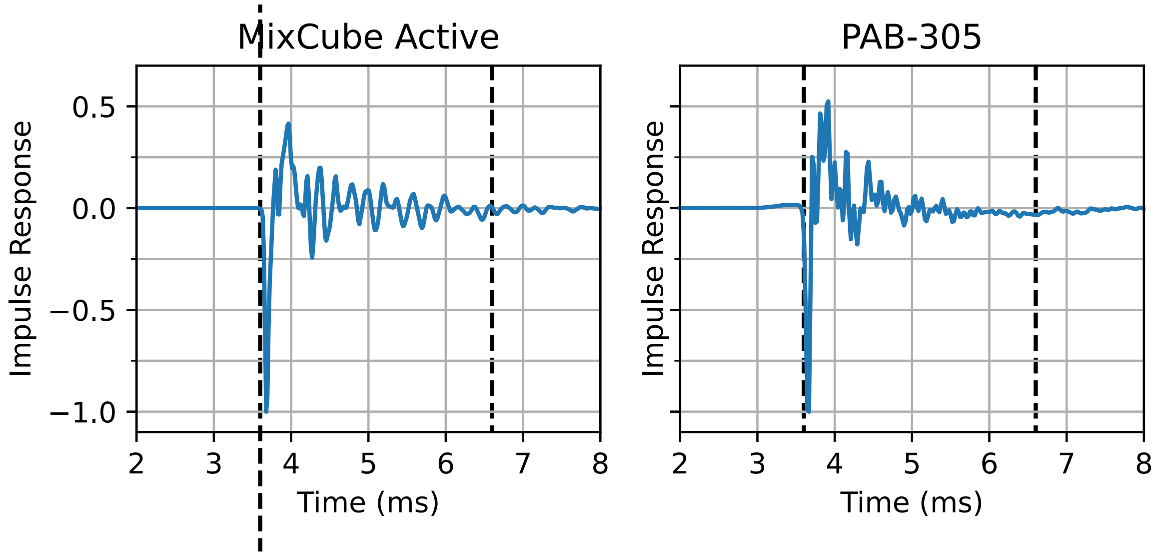


Figure 21. Comparison of the (normalized) impulse response of the Avantone MixCube Active and the img Stageline PAB-305 within a 3 ms window (black dashed lines).

Figure 22 shows the magnitude of the frequency response of the PAB-305 in comparison to the Avantone MixCube Active. The magnitude is normalized to 0 dB at 1 kHz to show the comparable flatness of the frequency response. The absolute power of both systems is sufficient for the measurements. Due to its bass reflex system, the PAB-305 shows more power in the low-frequency range, which may improve the SNR for quick-measurements of airborne sound insulation. Figure 23 shows the lightweight loudspeaker Img Stageline PAB-305/SW used for the measurements at the AIT laboratory in Vienna.

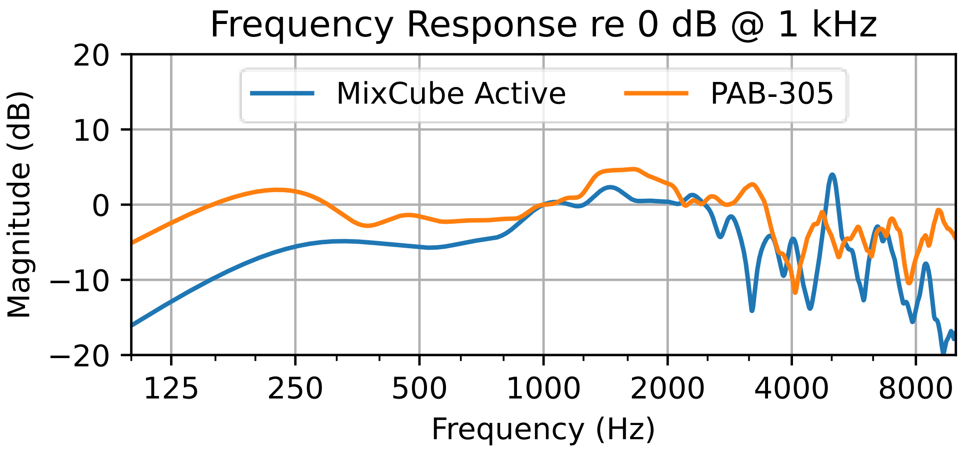


Figure 22. Comparison of the magnitude of the frequency response of the Avantone MixCube Active and the img Stageline PAB-305 in respect to 0 dB @ 1 kHz.

Figure 23. The lightweight loudspeaker Img Stageline PAB-305/SW used for the measurements at the AIT laboratory in Vienna.

4. SOPRA measurement procedure

4.1 Introduction

The SOPRA method is a quick test method for determining the intrinsic characteristics of sound absorption and airborne sound insulation of road traffic noise barriers under a direct sound field, i.e. in non-reverberant conditions. The methodology assess indirectly sound absorption by measuring sound reflection, its complementary characteristics.

The measuring procedure is borrowed with simplifications and with less changes as possible from EN 1793-5 and EN 1793-6, which are supposed to be known to the reader. Therefore, the procedure is summarized here in a compact way, referring to EN 1793-5 and EN 1793-6 whenever possible; only relevant changes from the standard EN procedure will be highlighted.

4.2 Sound absorption/reflection

4.2.1 General principle

The sound source emits a transient sound wave that travels past the microphone antenna position to the device under test and is then reflected on it (Figure 24). Each microphone, being placed between the sound source and the device under test, receives both the direct sound pressure wave travelling from the sound source to the device under test and the sound pressure wave reflected (including scattering) by the device under test. The direct sound pressure wave can be better acquired with a separate free field measurement keeping the same geometrical setup of sound source and microphone antenna but without the noise barrier (see Figure 25). The ratio of the power spectra of the direct and the reflected components gives the basis for calculating the “quick” sound reflection index.

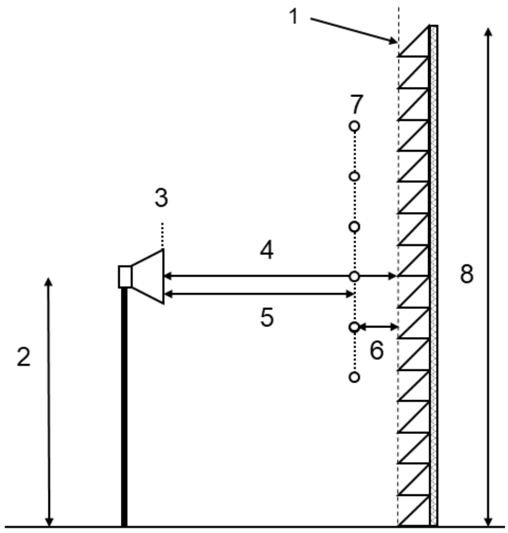


Figure 24. (not to scale) Sketch of the sound source and the microphone antenna in front of the road traffic noise reducing device under test for sound reflection index measurements.

Key

1 Source and microphone reference surface

2 Reference height h_S [m]

3 Loudspeaker front panel

4 Distance between the loudspeaker front panel and the reference surface, d_S [m]

5 Distance between the loudspeaker front panel and the microphone antenna, d_{SM} [m]

6 Distance between the microphone antenna and the reference surface, d_M [m]

7 Microphone antenna

8 Noise barrier height, h_B [m]

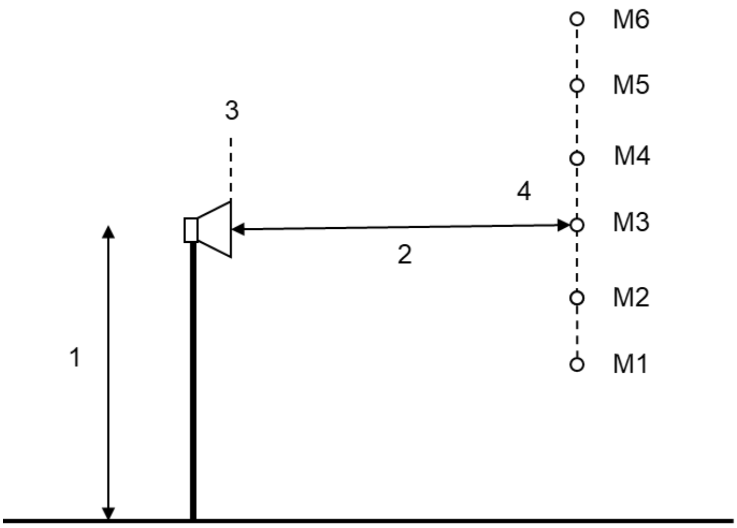


Figure 25. (not to scale) Sketch of the set-up for the reference "free-field" sound measurement for the determination of the sound reflection index. The microphones are labelled "M1" to "M6" from the bottom to the top.

Key

1 Reference height h_S [m]

2 Distance between the loudspeaker front panel and the microphone antenna d_{SM} [m]

3 Loudspeaker front panel

4 Microphone antenna

4.2.2 Measured quantity

The expression used to compute the "quick" reflection index RI_Q as a function of frequency, in the j-th one-third octave band, is:

$$RI_{Q,j} = \frac{1}{n_j}\sum_{k=1}^{n_j}\left[\frac{\int_{\Delta f_j}\left|F\left[h_{r,k}(t)\cdot w_{r,k}(t)\right]\right|^2 df}{\int_{\Delta f_j}\left|F\left[h_{i,k}(t)\cdot w_{i,k}(t)\right]\right|^2 df}\cdot C_{geo,k}\right] \quad (1)$$

where

$h_{i,k}(t)$ is the incident reference component of the free-field impulse response at the *k*-th measurement point;

$h_{r,k}(t)$ is the reflected component of the impulse response taken in front of the sample under test at the *k*-th measurement point;

$w_{i,k}(t)$ is the time window (Adrienne temporal window) for the incident reference component of the free-field impulse response at the *k*-th measurement point; see EN 1793-5:2016, point 5.5.5 [8].

$w_{r,k}(t)$ is the time window (Adrienne temporal window) for the reflected component at the *k*-th measurement point;

F is the symbol of the Fourier transform;

j	is the index of the one-third octave frequency bands (between 200 Hz and 5 kHz, where possible);
Δf_j	is the width of the j-th one-third octave frequency band;
k	is the microphone number according to Figure 25 (k = 1, ..., 6);
n_j	is the number of microphone positions on which to average;
$C_{geo,k}$	is the correction factor for geometrical divergence at the k-th measurement point;

The correction factors for geometrical divergence, $C_{geo,k}$, are given by:

$$C_{geo,k} = \left(\frac{d_{r,k}}{d_{i,k}}\right)^2 \tag{2}$$

where

$d_{i,k}$	is the distance from the front panel of the loudspeaker to the k-th microphone;
$d_{r,k}$	is the distance from the front panel of the loudspeaker to the source and microphone reference plane and back to the k-th microphone following specular reflection;
k	is the microphone number according to Figure 25 (k = 1, ..., 6).

NOTE For the microphone n. 3 (M3), $d_{i,5} = d_{SM}$ = 1,25 m. The spacing between adjacent microphones is s = 0,40 m.

4.2.3 Test arrangement

The quick method is intended to be applied on noise barriers installed alongside roads.

A reference surface for quick sound reflection index measurements is defined: it is an ideal, smooth surface facing the sound source side of the noise barrier under test and just touching the most protruding and significant parts of it within the tested area (see Figure 24).

The **sound source reference position** is a position facing the noise barrier side exposed to road traffic noise, located at the reference height h_S = 2,00 m and placed so that the horizontal distance of the source front panel to the reference surface of the noise barrier is d_S = 1,50 m (see Figure 24).

The **microphone antenna reference position** for quick sound reflection index measurements is a position compliant with all the following conditions: i) the microphone antenna is on the noise barrier side exposed to traffic noise; ii) the microphone n. 3 (M3) is located at the reference height h_S; iii) the shortest distance of the microphone n. 3 (M3) to the reference surface is d_M = 0,25 m (see Figure 24).

For non-flat noise barriers and non-flat inclined noise barriers see Figure 26.

For curved noise barriers, see Figure 27.

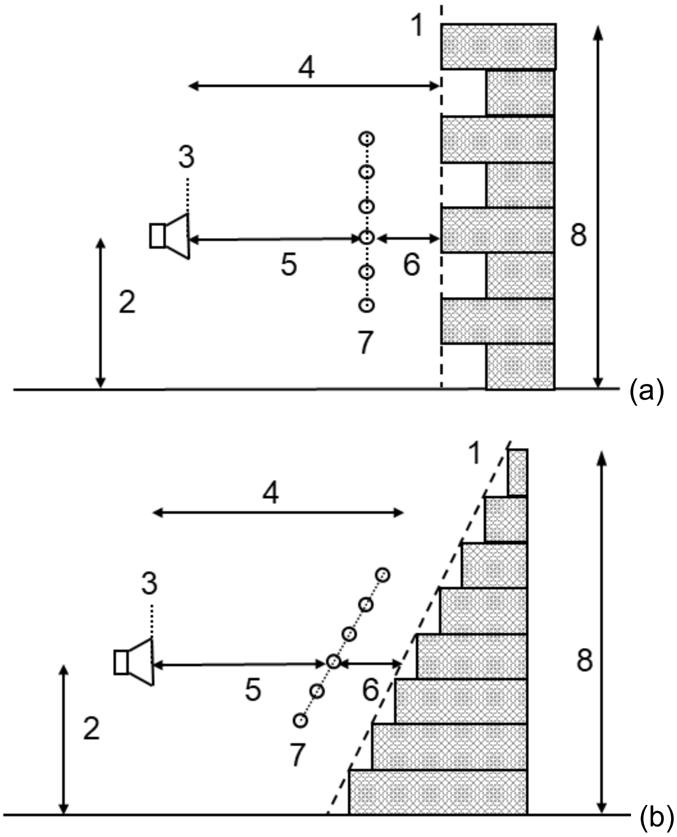


Figure 26. (not to scale) Sketch of the set-up for the quick reflection index measurement in front of (a): a vertical non-flat noise barrier; (b): an inclined non-flat noise barrier.

Key

1 Source and microphone reference surface	2 Reference height h_S [m]
3 Loudspeaker front panel	4 Distance between the loudspeaker front panel and the reference surface, d_S [m]
5 Distance between the loudspeaker front panel and the microphone antenna, d_{SM} [m]	6 Distance between the microphone antenna and the reference surface, d_M [m]
7 Microphone antenna	8 Noise barrier height, h_B [m]

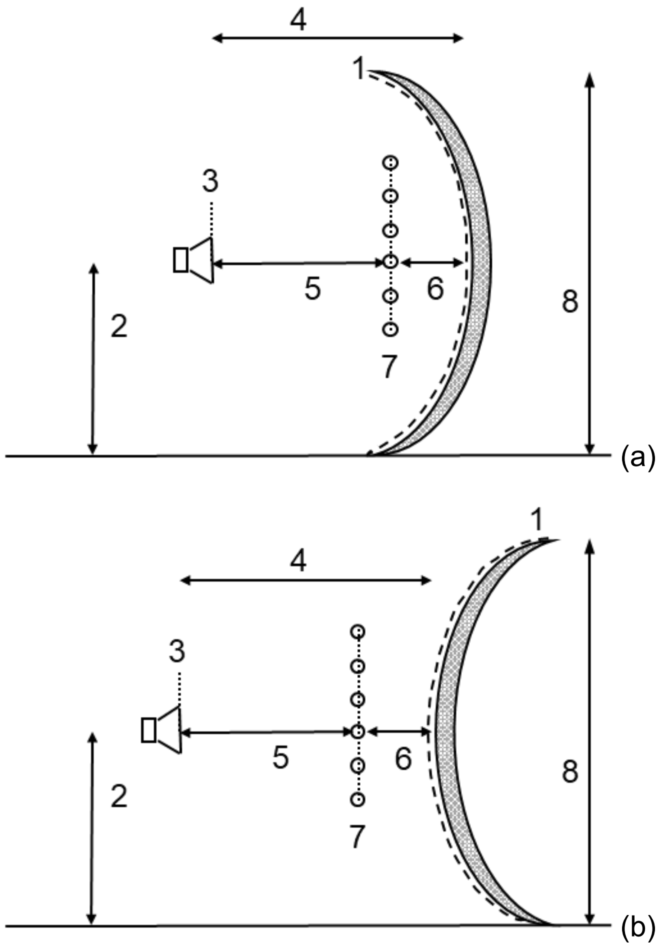


Figure 27. (not to scale) Sketch of the set-up for the quick reflection index measurement in front of (a): a concave noise barrier; (b): a convex noise barrier.

Key

1 Source and microphone reference surface	2 Reference height h_S [m]
3 Loudspeaker front panel	4 Distance between the loudspeaker front panel and the reference surface, d_S [m]
5 Distance between the loudspeaker front panel and the microphone antenna, d_{SM} [m]	6 Distance between the microphone antenna and the reference surface, d_M [m]
7 Microphone antenna	8 Noise barrier height, h_B [m]

4.2.4 Signal processing

Measurements are done in one-third octave bands between 200 Hz and 5 kHz.

The test signal is a maximum-length sequence (MLS). Any other full period of deterministic, flat-spectrum signal, like exponential sine sweep (ESS), can be used.

The sample rate shall have a value equal or greater than 44,1 kHz.

The overall impulse responses consist of a direct component, a component reflected from the surface under test and other parasitic reflections. The direct component and the reflected component from the device under test are extracted from the impulse response at each microphone position using suitable analysis windows in the time domain.

The windowing operations are performed using the Adrienne temporal window described in EN 1793-5 and keeping the same window width and positioning rules.

One measurement at each of the six microphones of the vertical antenna is done, independently of the shape and material composition of the noise barrier under test.

Then the single measurements are averaged as per formula (1).

The microphones to be considered in the processing stage as a function of the height of the noise barrier under test are given in Table 5.

The microphones used in the post-processing should be clearly identified in the report, stating their identification label (M1, M2, …, M6).

The bottom microphone (M1) is at an height of 1,20 m above ground. In this position it is influenced by the reflection on the ground and thus the analysis window should be reduced to avoid the unwanted reflection, inducing a higher low- frequency limit. That's why in Table 5 it is always in parentheses. If reputed useful for the particular composition of the noise barrier under test (e.g. different and sound absorbing material at the bottom of the noise barrier), the bottom microphone (M1) can still be used, knowing that the result could be interesting for a relative comparison of the different barrier fields, but cannot be compared with the full EN measurement.

Table 5: Microphones to be considered in the post-processing stage as a function of the height of the noise barrier under test.

Barrier height, H_B	Microphones	Lowest reliable one-third octave frequency band
$H_B \leq 3$ m	(M1) M2 to M4	315 Hz
3 m < $H_B \leq 4$ m	(M1) M2 to M5	250 Hz
4 m < $H_B \leq 5$ m	(M1) M2 to M5	250 Hz
5 m < $H_B \leq 6$ m	(M1) M2 to M6	200 Hz
H_B > 6 m and over	(M1) M2 to M6	200 Hz

4.2.5 Safety considerations

The application of the quick method may involve hazardous operations, because measurements are made on or aside roads in use. This document does not purport to address all of the safety problems associated with its use. It is the responsibility of the user of this document to establish appropriate safety and health practices based on a risk assessment and determine the applicability of regulatory limitations prior to use.

4.2.6 Wind and air temperature

Wind speed at microphone positions shall not exceed 5 m/s during the measurements.

The ambient air temperature shall be within 0-40 °C during the measurements. In calculations involving the sound speed value, its temperature-dependent value shall be taken, using the actual temperature value around the test area.

4.2.7 Single-number rating of sound absorption under a direct sound field DL_{RIQ}

A single-number rating can be derived to indicate the performance of the product. In this case, the individual quick sound reflection index values are weighted according to the normalized traffic noise spectrum defined in EN 1793-3.

The single-number rating of sound absorption under a direct sound field DL_{RIQ}, in decibels, is given by:

$$DL_{RIQ} = -10 \cdot lg\left[\frac{\sum_{i=m}^{15} RI_i \cdot 10^{0,1L_i}}{\sum_{i=m}^{15} 10^{0,1L_i}}\right] \tag{3}$$

where

m number of the lowest reliable one-third octave frequency band;

L_i relative A-weighted sound pressure levels (dB) of the normalized traffic noise spectrum, as defined in EN 1793–3, in the i-th one-third octave band.

In some cases the ratio of the summation terms in the expression of DL_{RIQ} can exceed 1 which precludes the correct calculation of DL_{RIQ}. For this reason the maximum value of this ratio shall be limited to 0,99.

4.2.8 Measurement uncertainty of RI_Q

The statement of an analytical model of the quick sound reflection index RI_Q as a function of many input variables in compliance with ISO/IEC Guide 98-3 seems, at the state of the art of the knowledge, not feasible.

Therefore, values for the standard deviation of reproducibility, when available, may be used as an estimate of the combined standard uncertainty of determinations of the quick sound reflection index. To this purpose an inter-laboratory test should be done; however, this is beyond the scope of the SOPRANOISE project.

What can be said at this stage is the will of some partners of the project to continue investigating the repeatability and reproducibility of the method after the end of the project.

4.3 Sound insulation

4.3.1 General principle

The sound source emits a transient sound wave that travels toward the device under test and is partly reflected, partly transmitted and partly diffracted by it. The microphone placed on the other side of the device under test receives both the transmitted sound pressure wave travelling from the sound source through the device under test, and the sound pressure wave diffracted by the top edge of the device under test (Figure 28). If the measurement is repeated without the device under test between the loudspeaker and the microphone, the direct free-field wave can be acquired (Figure 29). The power spectra of the direct wave and the transmitted wave give the basis for calculating the “quick” sound insulation index.

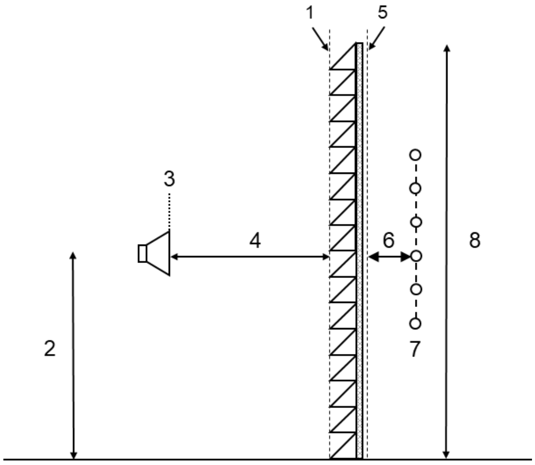


Figure 28. (not to scale) Sketch of the sound source and the microphone antenna close to the noise barrier under test for quick sound insulation index measurements.

Key

1	Sound source reference surface	5	Microphone reference surface
2	Sound source reference height, h_S [m]	6	Distance between the microphone antenna and the microphone reference surface, d_M [m]
3	Loudspeaker front panel	7	Microphone antenna
4	Distance between loudspeaker front panel and source reference surface, d_S [m]	8	Noise barrier height, h_B [m]

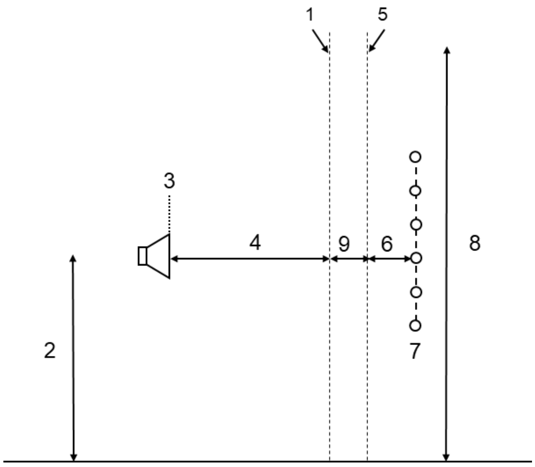


Figure 29. (not to scale) Sketch of the of the set-up for the reference “free-field” sound measurement for the determination of the quick sound insulation index.

Key

1	Sound source reference surface	5	Microphone reference surface
2	Sound source reference height, h_S [m]	6	Distance between the microphone antenna and the microphone reference surface, d_M [m]
3	Loudspeaker front panel	7	Microphone antenna
4	Distance between loudspeaker front panel and source reference surface, d_S [m]	8	Noise barrier height, h_B [m]
9	Nominal noise barrier thickness, t_B [m]		

4.3.2 Measured quantity

The expression used to compute the "quick" sound insulation index $SI_{Q,j}$ as a function of frequency, in the j-th one-third octave band, is:

$$SI_{Q,j} = -10 \cdot lg\left\{\frac{1}{n}\sum_{k=1}^{n}\frac{\int_{\Delta f_j}\left|F\left[h_{t,k}(t)w_{t,k}(t)\right]\right|^2 df}{\int_{\Delta f_j}\left|F\left[h_{i,k}(t)w_{i,k}(t)\right]\right|^2 df}\right\} \tag{4}$$

where

$h_{i,k}(t)$	is the incident reference component of the free-field impulse response at the k_{th} scanning point;
$h_{t,k}(t)$	is the transmitted component of the impulse response at the k^{th} scanning point;
$w_{i,k}(t)$	is the time window (Adrienne temporal window) for the incident reference component of the free-field impulse response at the k^{th} scanning point;
$w_{t,k}(t)$	is the time window (Adrienne temporal window) for the transmitted component at the k^{th} scanning point;
F	is the symbol of the Fourier transform;
j	is the index of the j^{th} one-third octave frequency band (between 200 Hz and 5 kHz, where possible);
Δf_j	is the width of the jth one-third octave frequency band;
$n = 6$	is the number of scanning points.

4.3.3 Test arrangement

The quick method is intended to be applied on noise barriers installed alongside roads.

A sound source reference surface for quick sound insulation index measurements is defined: it is an ideal, smooth surface facing the sound source side of the road traffic noise barrier under test and just touching the most protruding and significant parts of it within the tested area (see Figure 28). A microphone reference surface for quick sound insulation index measurements is defined: it is an ideal, smooth surface facing the back side of the road traffic noise barrier under test and just touching the most protruding and significant parts of it within the tested area (see Figure 28).

The **sound source reference position** for quick sound insulation index measurements is a position facing the noise barrier side exposed to road traffic noise, located at the reference height h_S = 2,00 m and placed so that the horizontal distance of the loudspeaker front panel to the reference surface of the noise barrier is d_S = 1,00 m (see Figure 28).

The **microphone antenna reference position** for quick sound insulation index measurements is a position compliant with all the following conditions: i) the microphone antenna is on the noise barrier back side, not exposed to traffic noise; ii) the microphone n. 3 (M3) is located at the reference height h_S; iii) the shortest distance of the microphone n. 3 (M3) to the microphone reference surface is d_M = 0,25 m (see Figure 28).

For non-flat noise barriers and/or inclined noise barriers see Figure 30.

For curved noise barriers, see Figure 31.

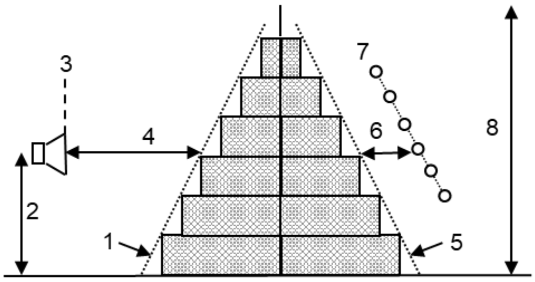
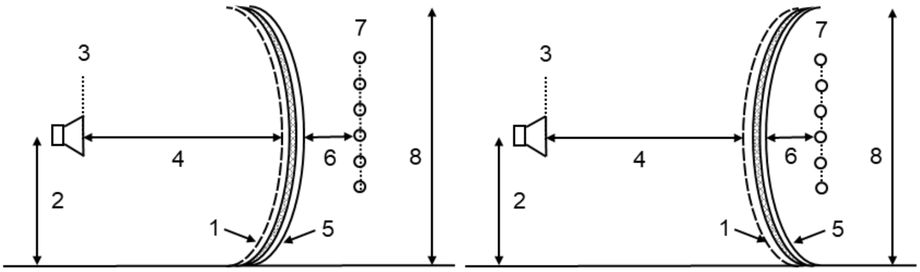


Figure 30. (not to scale) Sketch of the set-up for the quick sound insulation index measurement in front of an inclined and non-flat noise barrier.

Key

1	Sound source reference surface	5	Microphone reference surface
2	Sound source reference height, h_S [m]	6	Distance between the microphone antenna and the microphone reference surface, d_M [m]
3	Loudspeaker front panel	7	Microphone antenna
4	Distance between the loudspeaker front panel and source reference surface, d_S [m]	8	Noise barrier height, h_B [m]



(a

(b)

Figure 31. (not to scale) Sketch of the set-up for the quick sound insulation index measurement in front of; (a): a concave noise barrier; (b): a convex noise barrier.

Key

1	Sound source reference surface	5	Microphone reference surface
2	Sound source reference height, h_S [m]	6	Distance between the microphone antenna and the microphone reference surface, d_M [m]
3	Loudspeaker front panel	7	Microphone antenna
4	Distance between the loudspeaker front panel and source reference surface, d_S [m]	8	Noise barrier height, h_B [m]

4.3.4 Signal processing

Measurements are done in one-third octave bands between 200 Hz and 5 kHz.

The test signal is a maximum-length sequence (MLS). Any other full period of deterministic, flat-spectrum signal, like exponential sine sweep (ESS), can be used.

The sample rate shall have a value equal or greater than 44,1 kHz.

The overall impulse responses acquired with sound source and microphone antenna on the opposite sides of the noise barrier consist of a component transmitted through the noise barrier under test, a component diffracted over the top edge and other parasitic reflections. The overall impulse responses acquired in the free filed consist of a direct component and other parasitic reflections. The direct component and the transmitted component from the device under test are extracted from the impulse response at each microphone position using suitable analysis windows in the time domain.

The windowing operations are performed using the Adrienne temporal window described in EN 1793-6 and keeping the same window width and positioning rules.

One measurement at each of the six microphones of the vertical antenna is done, independently of the shape and material composition of the noise barrier under test.

Then the single measurements are averaged as per formula (4).

The microphones to be considered in the processing stage as a function of the height of the noise barrier under test ae given in Table 6.

The bottom microphone (M1) is at an height of 1,20 m above ground. In this position it is influenced by the reflection on the ground and thus the analysis window should be reduced to avoid the unwanted reflection, inducing a higher low- frequency limit. That's why in Table 6 it is always in parentheses. If reputed useful for the particular composition of the noise barrier under test (e.g. different and sound absorbing material at the bottom of the noise barrier), the bottom microphone (M1) can still be used, knowing that the result could be interesting for a relative comparison of the different barrier fields, but cannot be compared with the full EN measurement.

Table 6: Microphones to be considered in the post-processing stage as a function of the height of the noise barrier under test.

Barrier height, H_B	Microphones	Lowest reliable one-third octave frequency band
$H_B \leq 3$ m	(M1) M2 to M4	315 Hz
3 m < $H_B \leq 4$ m	(M1) M2 to M5	250 Hz
4 m < $H_B \leq 5$ m	(M1) M2 to M5	250 Hz
5 m < $H_B \leq 6$ m	(M1) M2 to M6	200 Hz
H_B > 6 m and over	(M1) M2 to M6	200 Hz

4.3.5 Safety considerations

The application of the quick method may involve hazardous operations, because measurements are made on or aside roads in use. This document does not purport to address all of the safety problems associated with its use. It is the responsibility of the user of this document to establish appropriate safety and health practices based on a risk assessment and determine the applicability of regulatory limitations prior to use.

4.3.6 Wind and air temperature

Wind speed at microphone positions shall not exceed 5 m/s during the measurements.

The ambient air temperature shall be within 0-40 °C during the measurements. In calculations involving the sound speed value, its temperature-dependent value shall be taken, using the actual temperature value around the test area.

4.3.7 Single-number rating of sound insulation under a direct sound field DL_{SIQ}

A single-number rating can be derived to indicate the performance of the product. In this case, the individual quick sound insulation index values are weighted according to the normalized traffic noise spectrum defined in EN 1793-3.

The single-number rating of sound insulation under a direct sound field DL_{SIQ}, in decibels, is given by:

$$DL_{SIQ} = -10 \cdot lg \left[\frac{\sum_{i=m}^{15} 10^{-0,1 SI_{Q,i}} \cdot 10^{0,1 L_i}}{\sum_{i=m}^{15} 10^{0,1 L_i}} \right] \quad (5)$$

where

m number of the lowest reliable one-third octave frequency band;

L_i relative A-weighted sound pressure levels (dB) of the normalized traffic noise spectrum, as defined in EN 1793–3, in the i-th one-third octave band.

4.3.8 Measurement uncertainty of SI_Q

The statement of an analytical model of the quick sound insulation index SI_Q as a function of many input variables in compliance with ISO/IEC Guide 98-3 seems, at the state of the art of the knowledge, not feasible.

Therefore, values for the standard deviation of reproducibility, when available, may be used as an estimate of the combined standard uncertainty of determinations of the quick sound insulation index. To this purpose an inter-laboratory test should be done; however, this is beyond the scope of the SOPRANOISE project.

What can be said at this stage is the will of some partners of the project to continue investigating the repeatability and reproducibility of the method after the end of the project.

5. In-situ tests done by UNIBO along the A22 motorway

5.1 Metal noise barriers

5.1.1. The noise barrier under test

The noise barrier under test is made up of modular aluminum panels with the road side face perforated and the external face solid. The barrier is built by overlapping several panels of the same length, equal to 3,00 m, and with a height of 0,50 m, on a porous concrete curb 1,00 m high. The panels are inserted into HEA 180 posts spaced 2,67 m apart. The overall height of the barrier is 5,00 m. The barrier is about two years old. See Figure 32.

Each modular panel is composed of:

- rear casing in aluminum sheet, Al-Mg-Mn 3105 alloy, painted after all processing stages, nominal sheet thickness 1,2 mm;

- bitumen soundproofing sheet, nominal thickness 2 mm and nominal surface mass 3 kg/m²;

- bitumen soundproofing sheet, nominal thickness 4 mm and nominal surface mass 5 kg/m²;

- internal insulation consisting of a polyester fiber mat, nominal thickness 90 mm and nominal density 40 kg/m³;

- front casing in aluminum sheet, Al-Mg-Mn 3105 alloy, nominal thickness 1,2 mm, painted after all processing stages with holes in n. 6 different diameters, nominal diameter 2,5 ÷ 7 mm and nominal drilling percentage 34%;

- closing caps of the panel heads with gasket, in rigid molded polypropylene, mechanically fixed to the panel itself;

- double mechanical joint of the male-female type, without the interposition of gaskets.

Figure 32. View of the barrier under test from the side facing the traffic.

5.1.2. Quick sound reflection index measurements

In one day, from about 10 AM to 16 PM, twenty-two quick reflection index tests and eleven quick sound insulation tests have been done.

The quick reflection index tests have been done placing the linear antenna and the lightweight loudspeaker in twenty different positions facing a field (post-to-post span) on the road traffic side of the noise barrier. Two of these measurements were repeated twice for control. See Figure 33. The raw data have been processed, considering: i) all the six microphones (height above ground from 1,20 m to 3,20 m); ii) the five microphones from M1 to M5 (height above ground from 1,20 m to 2,80 m); iii) the four microphones from M2 to M5 (height above ground from 1,60 m to 2,80 m).The loudspeaker was at an height of 2,00 m above ground.

Three months before this test, a field of the same noise barrier was measured applying the full EN 1793-5 procedure with the standard equipment.

Figure 33. Microphone antenna, loudspeaker and control device in place for the quick sound reflection index measurements.

Figure 34 presents the results of all 22 quick measurements, averaged over **all six microphones** (M1 to M6), the results of a full EN 1793-5 test done 3 months before and the tolerance interval; the latter is defined by adding or subtracting to/from the EN 1793-5 measured value the expanded measurement uncertainty at 95% confidence level, U_{95}. It can be seen that the general trend of the full EN measurement is captured by the quick method; however, the measured quick reflection index values tend to be overestimated below the 500 Hz one-third octave band.

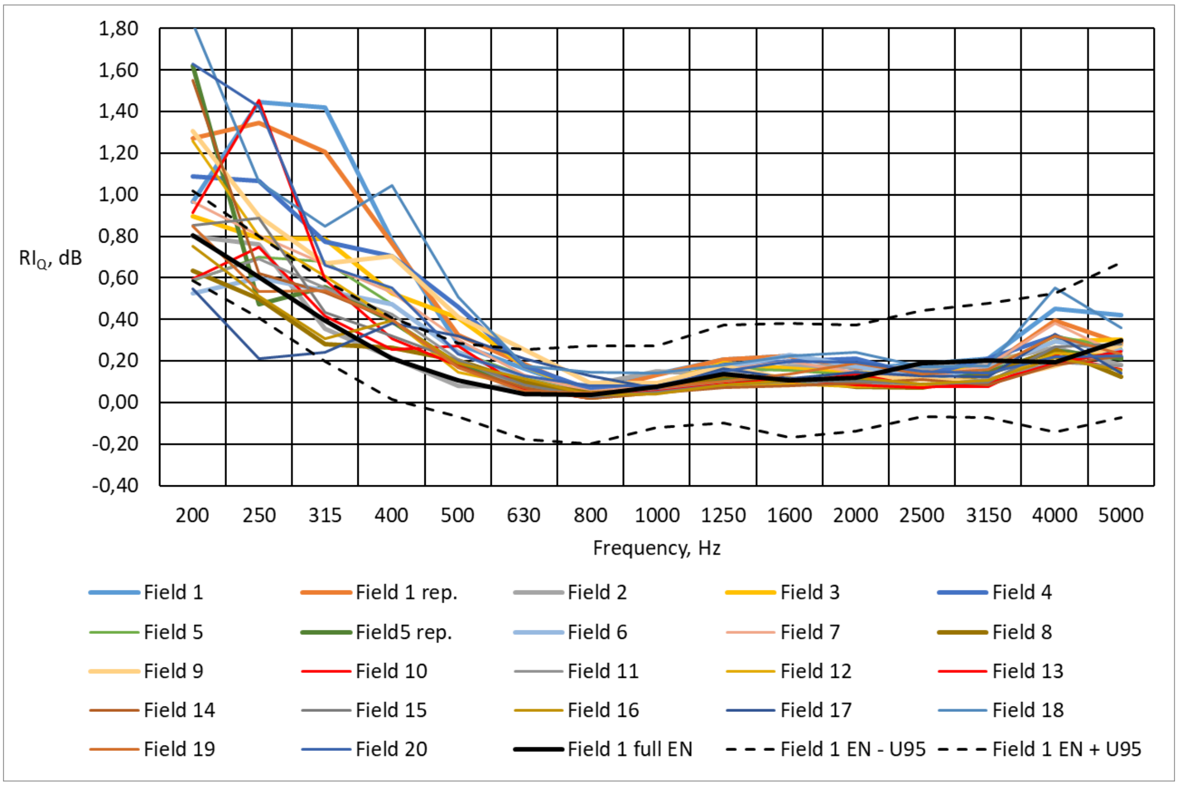


Figure 34. Colour lines: RI_Q spectra obtained with the quick method on the metal noise barrier for 20 different fields (2 repeated). Average over microphones M1-M6. Black continuous line: result of a previous EN 1793-5 measurement on a single field. Black dashed lines: EN 1793-5 measured value ± the expanded measurement uncertainty at 95% confidence level.

Figure 35 presents the results of all 22 quick measurements, averaged over **the five microphones M1 to M5** (excluding the top microphone, M6), the results of a full EN 1793-5 test done 3 months before and the tolerance interval; the latter is defined by adding or subtracting to/from the EN 1793-5 measured value the expanded measurement uncertainty at 95% confidence level, U_{95}. It can be seen that the general trend of the full EN measurement is captured better than before; however, the measured quick reflection index values still tend to be overestimated below the 500 Hz one-third octave band.

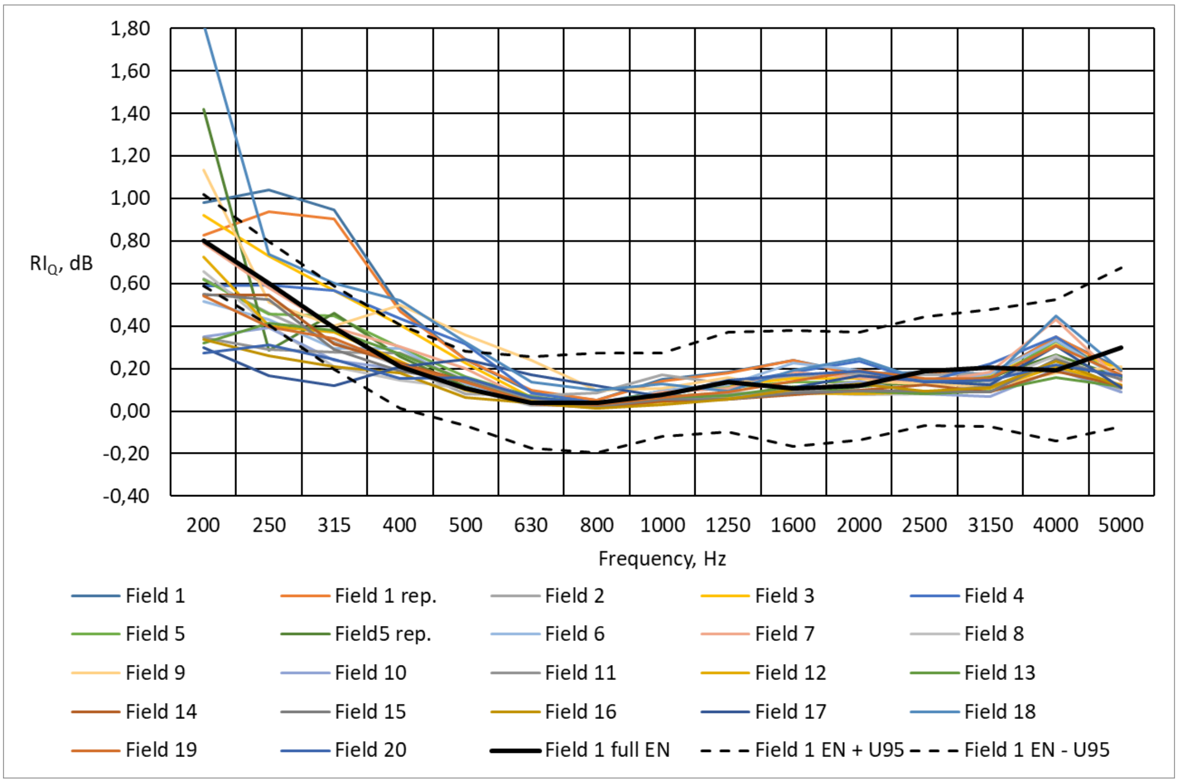


Figure 35. Colour lines: RI_Q spectra obtained with the quick method on the metal noise barrier for 20 different fields (2 repeated). Average over microphones M1-M5. Black continuous line: result of a previous EN 1793-5 measurement on a single field. Black dashed lines: EN 1793-5 measured value ± the expanded measurement uncertainty at 95% confidence level.

Figure 36 presents the results of all 22 quick measurements, averaged over the **four microphones M2 to M5** (excluding the bottom microphone, M1, and the top microphone, M6), the results of a full EN 1793-5 test done 3 months before and the tolerance interval defined by adding or subtracting to/from the EN 1793-5 measured value the measurement uncertainty at 95% confidence level. The general trend of the full EN measurement is captured better than before (Figure 34 and Figure 35; note that the y-scale has been changed). This proofs that for a noise barrier with a height in the range 4-5 m, when the antenna is simply placed on the ground, it is better to exclude the bottom microphone, too much influenced by the reflection of the sound waves emitted by the loudspeaker over the ground, and the top microphone, too much influenced by the sound waves emitted by the loudspeaker and diffracted back by the top edge to the microphone. If reputed useful for the particular composition of the barrier under test, the bottom microphone (M1) can still be used, knowing that the result could be interesting for a relative comparison of the different barrier fields, but cannot be compared with the full EN measurement.

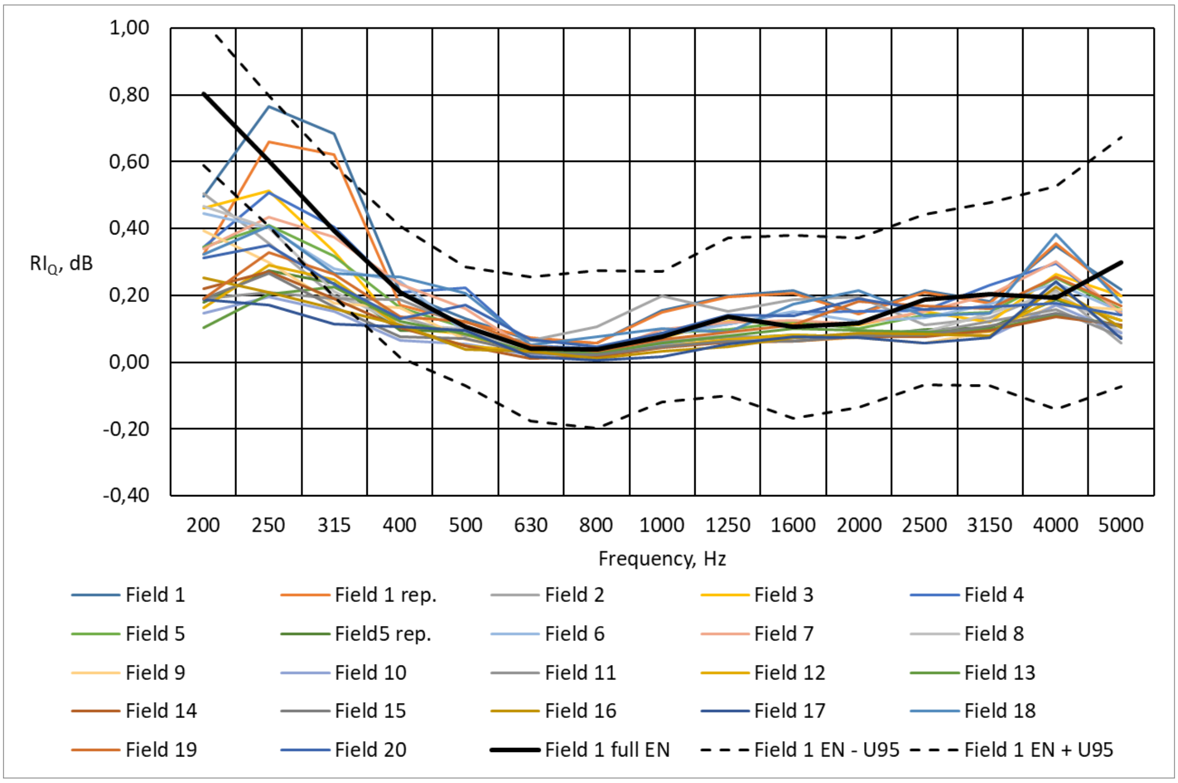


Figure 36. Colour lines: RI_Q spectra obtained with the quick method on the metal noise barrier for 20 different fields (2 repeated). Average over mic. M2-M5. Black continuous line: result of a previous EN 1793-5 measurement on a single field. Black dashed lines: EN 1793-5 measured value ± the expanded measurement uncertainty at 95% confidence level.

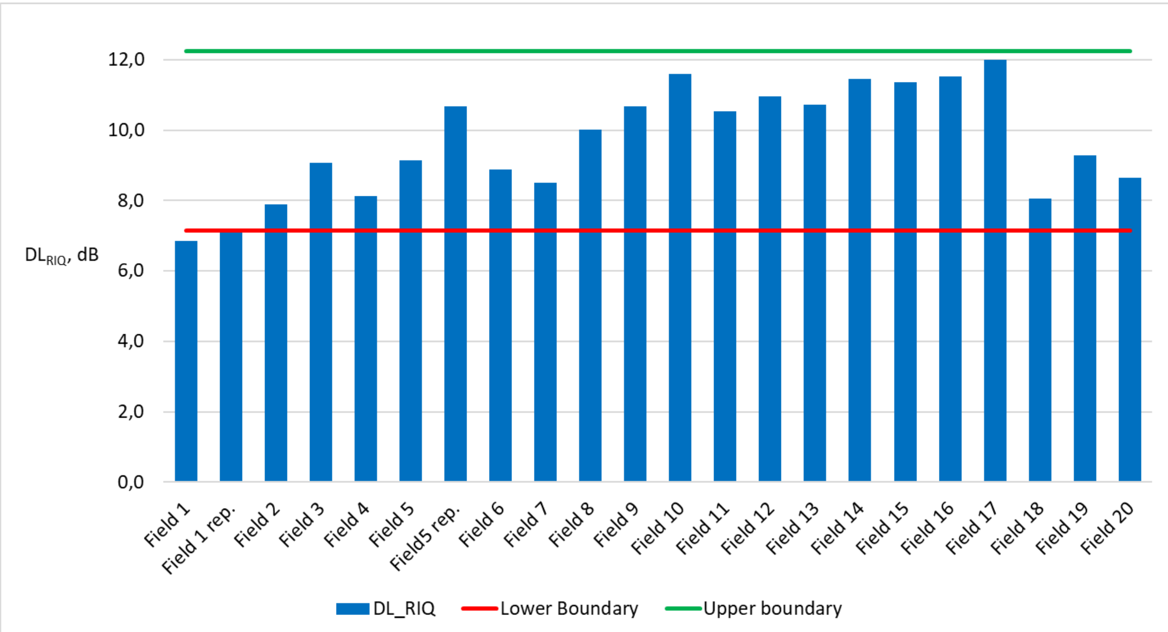


Figure 37. Differences of the single-number ratings of the individual RI_Q measurements on 20 different fields (plus 2 repetitions) from their average value. The lower and upper boundary lines are calculated as the mean ±1,645 times the standard deviation of the 22 measurements.

Figure 37 shows the differences of the single-number ratings of the individual RI_Q measurements on 20 different fields (plus 2 repetitions) from their mean value. The lower and upper boundary lines are calculated multiplying the standard deviation of the 22 values by ±1,645, which are the values of the abscissa of a standardized Gaussian distribution corresponding to a 90% coverage probability (bilateral).

This figure points out the actual differences existing among the different fields of a noise barrier in good conditions. Due to the combined variance of manufacturing, installation workmanship, etc., the single-number rating values range from 6,9 dB to 12,0 dB. **Only a quick method, allowing to do multiple measurements in a short time, can give this information.** A visual inspection cannot appreciate this variance: it would conclude that all fields are very similar and in good order and thus should get the same single-number rating. See Figure 38.

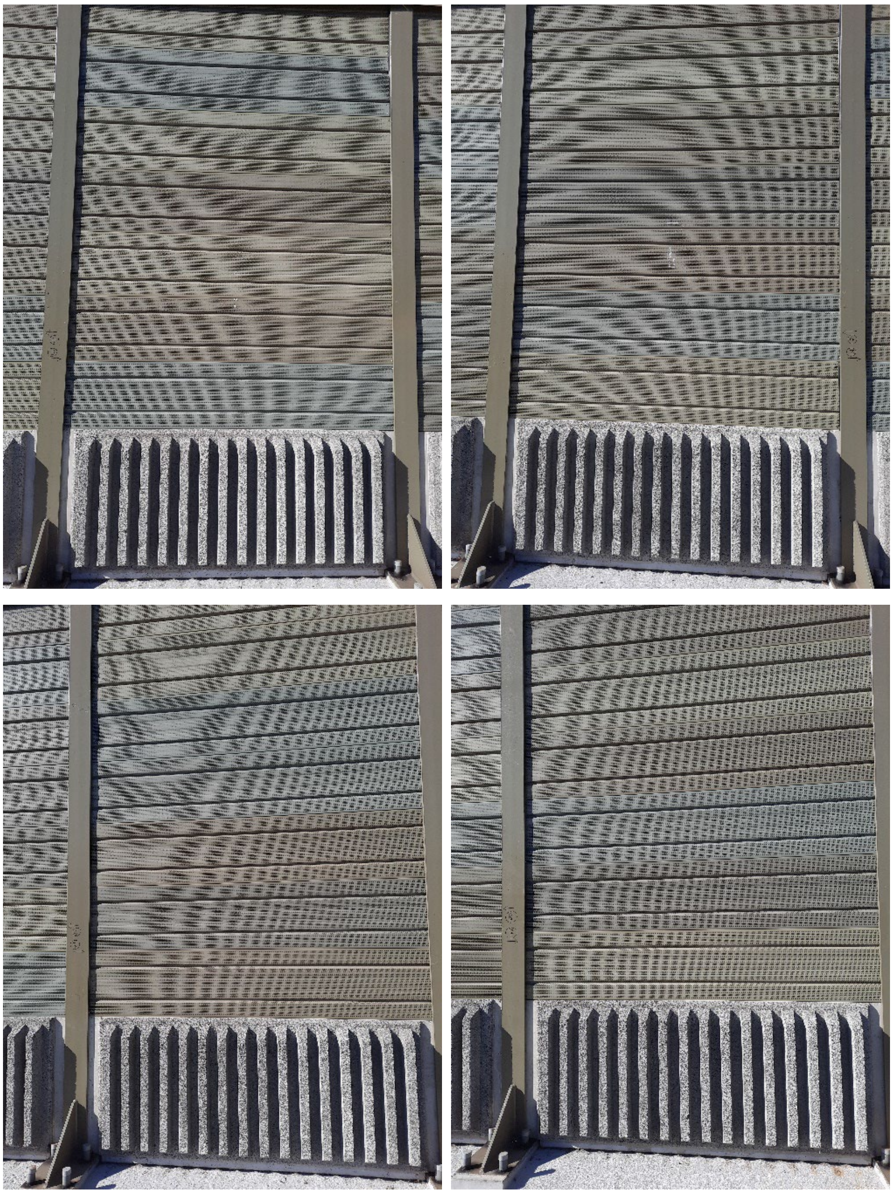


Figure 38. Pictures of some of the measured fields of the metal noise barrier under test.

The lower and upper boundary lines in Figure 37 are a first attempt to establish an acceptance criterion. The mean value of the single-number rating is 9,7 dB, with a standard deviation of 1,55 dB. As a reasonable guess, one could assume that some variability is acceptable, but not below the lower boundary line, corresponding to the statistical average of measured values minus 1,645 times the standard deviation (i.e. 7,15 dB). In principle, this criterion would reject the worst 5% of the fields. Actually, in the measured sample of 22 items, it would reject one field (n. 1); 1 over 22 is very close to 5%. However, it is remarked that the “rejected” field still has a good performance (DL_{RIQ} = 6,9 dB); the final decision should be taken after a full EN 1793-5 test done on this noise barrier field.

5.1.3. Quick sound insulation index measurements

As previously said, in one day, from about 10 AM to 16 PM, twenty-two quick reflection index tests and eleven quick sound insulation tests have been done.

The quick sound insulation index tests have been done placing the linear antenna and the lightweight loudspeaker on the opposite sides of ten different fields of the noise barrier; one measurement was repeated twice for control. See Figure 39 and Figure 40. The raw data have been processed, considering: i) all the six microphones (height above ground from 1,20 m to 3,20 m); ii) the five microphones from M1 to M5 (height above ground from 1,20 m to 2,80 m); iii) the four microphones from M2 to M5 (height above ground from 1,60 m to 2,80 m). The loudspeaker was at a height of 2,00 m above ground.

Three months before this test, a field of the same noise barrier was measured applying the full EN 1793-6 procedure with the standard equipment.

Figure 39. Microphone antenna and control device in place for the quick sound insulation index measurements.

Figure 40. Loudspeaker in place for the quick sound insulation index measurements.

Figure 41 presents the results of all 11 quick measurements, averaged over **all six microphones** (M1 to M6), the results of a full EN 1793-6 test done 3 months before and the tolerance interval; the latter is defined by adding or subtracting to/from the EN 1793-5 measured value the expanded measurement uncertainty at 95% confidence level, U_{95}. It can be seen that the general trend of the full EN measurement is captured by the quick method; however, the measured values are clearly underestimated over the full frequency range. This is due to the diffracted energy that travels over the top edge of the noise barrier and arrives at microphone 6.

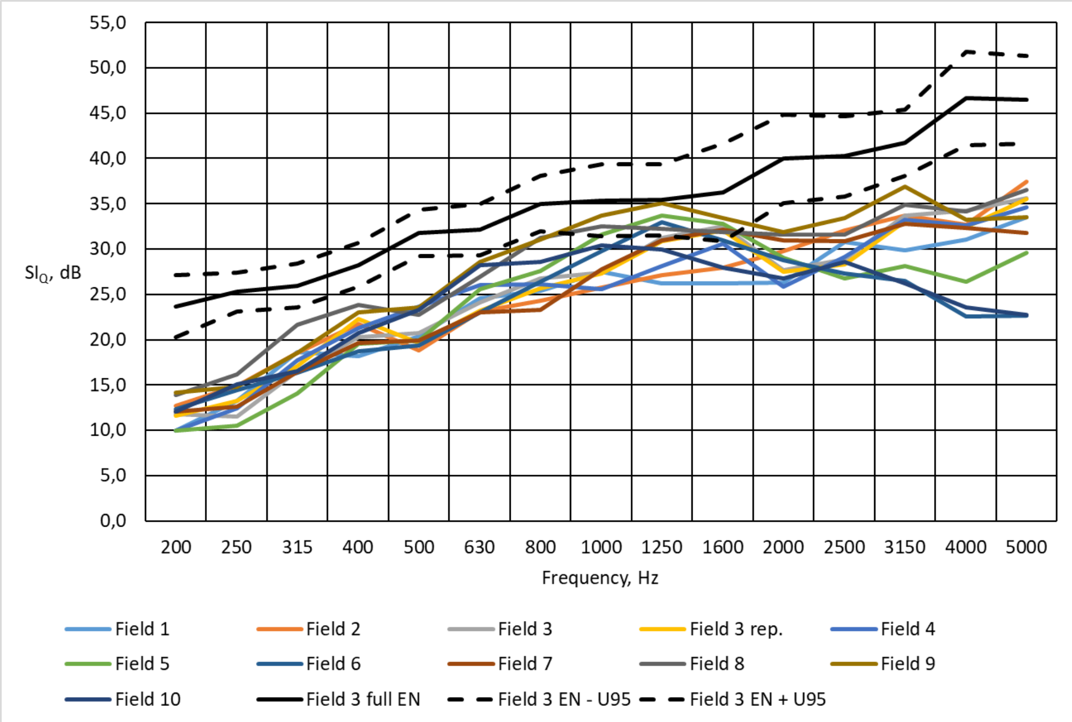


Figure 41. Colour lines: SI_Q spectra obtained with the quick method on the metal noise barrier for 10 different fields (1 tested twice). Average over microphones M1-M6. Black continuous line: result of a previous EN 1793-6 measurement on a single field. Black dashed lines: EN 1793-6 measured value ± the expanded measurement uncertainty at 95% confidence level.

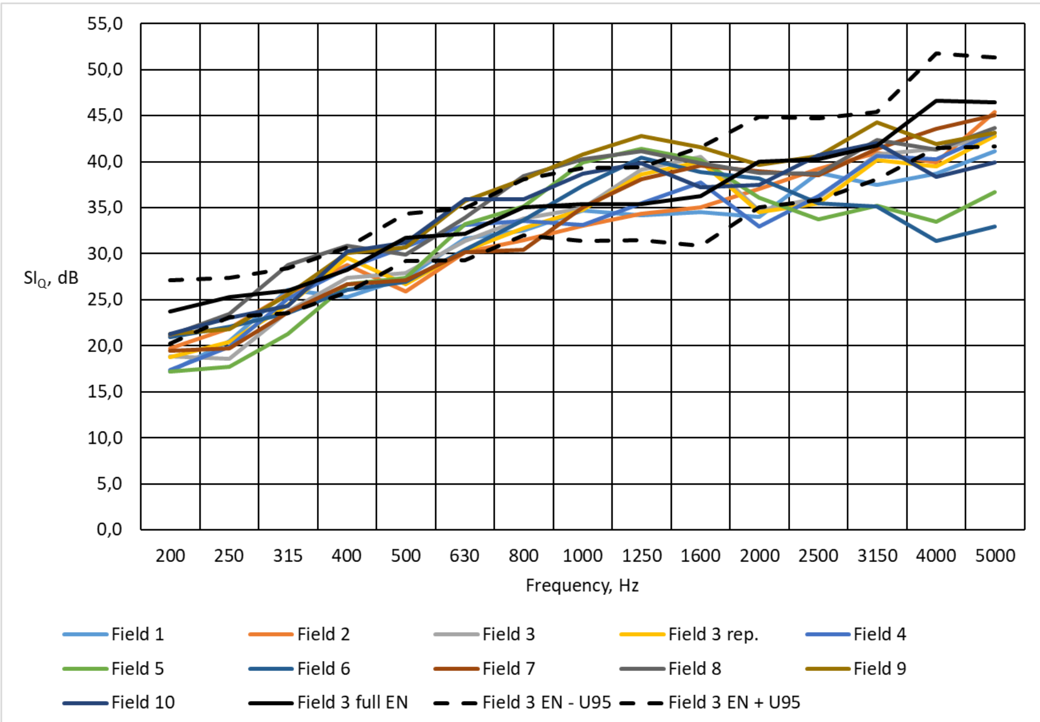


Figure 42. Colour lines: SI_Q spectra obtained with the quick method on the metal noise barrier for 10 different fields (1 tested twice). Average over microphones M1-M5. Black continuous line: result of a previous EN 1793-6 measurement on a single field. Black dashed lines: EN 1793-6 measured value ± the expanded measurement uncertainty at 95% confidence level.

Figure 42 presents the results of all 11 quick measurements, averaged over **the five microphones M1 to M5** (excluding the highest microphone, M6), the results of a full EN 1793-6 test done 3 months before and the tolerance interval; the latter is defined by adding or subtracting to/from the EN 1793-5 measured value the expanded measurement uncertainty at 95% confidence level, U_{95}. It can be seen that the general trend of the full EN measurement is captured better than before; however, the measured values are still underestimated at the lowest and highest frequencies.

Figure 43 presents the results of all 11 quick measurements, averaged over the **four microphones M2 to M5** (excluding the lowest microphone, M1, and the highest microphone, M6), the results of a full EN 1793-6 test done 3 months before and the tolerance interval defined by adding or subtracting to/from the EN 1793-6 measured value the measurement uncertainty at 95% confidence level. The general trend of the full EN measurement is captured and there is les bias compared to the preceding situations (Figure 41 and Figure 42). This proofs that for a noise barrier with an height in the range 4-5 m, when the antenna is simply placed on the ground, it is better to exclude the bottom microphone, too much influenced by the reflection of the sound waves emitted by the loudspeaker over the ground, and the top microphone, too much influenced by the sound waves emitted by the loudspeaker and diffracted back by the top edge to the microphone. This latter effect is particularly detrimental for airborne sound insulation.

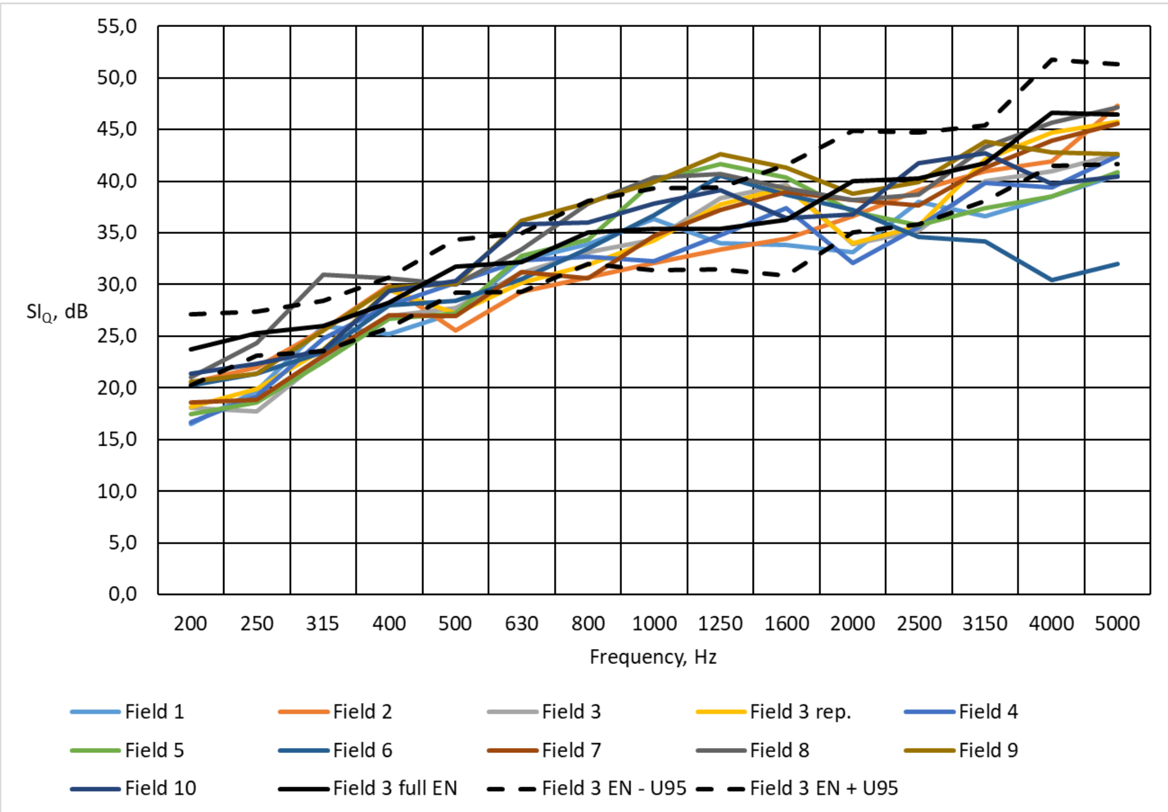


Figure 43. Colour lines: SI_Q spectra obtained with the quick method on the metal noise barrier for 10 different fields (1 tested twice). Average over microphones M2-M5. Black continuous line: result of a previous EN 1793-6 measurement on field n. 1. Black dashed lines: EN 1793-6 measured value plus or minus the expanded measurement uncertainty at 95% confidence level.

Figure 44 shows the differences of the single-number ratings of the individual SI_Q measurements on 10 different fields (1 tested twice) from their mean value. The lower and upper boundary lines are calculated multiplying the standard deviation of the measured values by ±1,645, which are the values of the abscissa of a standardized Gaussian distribution corresponding to a 90% coverage probability (bilateral).

This figure point out the actual differences existing among the different fields of a noise barrier in good conditions. Due to the combined variance of manufacturing, installation workmanship, etc., the single-number rating values range from 27,9 dB to 31,2 dB. **Only a quick method, allowing to do multiple measurements in a short time, can give this information**. A visual inspection cannot appreciate this variance: it would conclude that all fields are similar and in good order and thus should get the same single-number rating. See Figure 45.

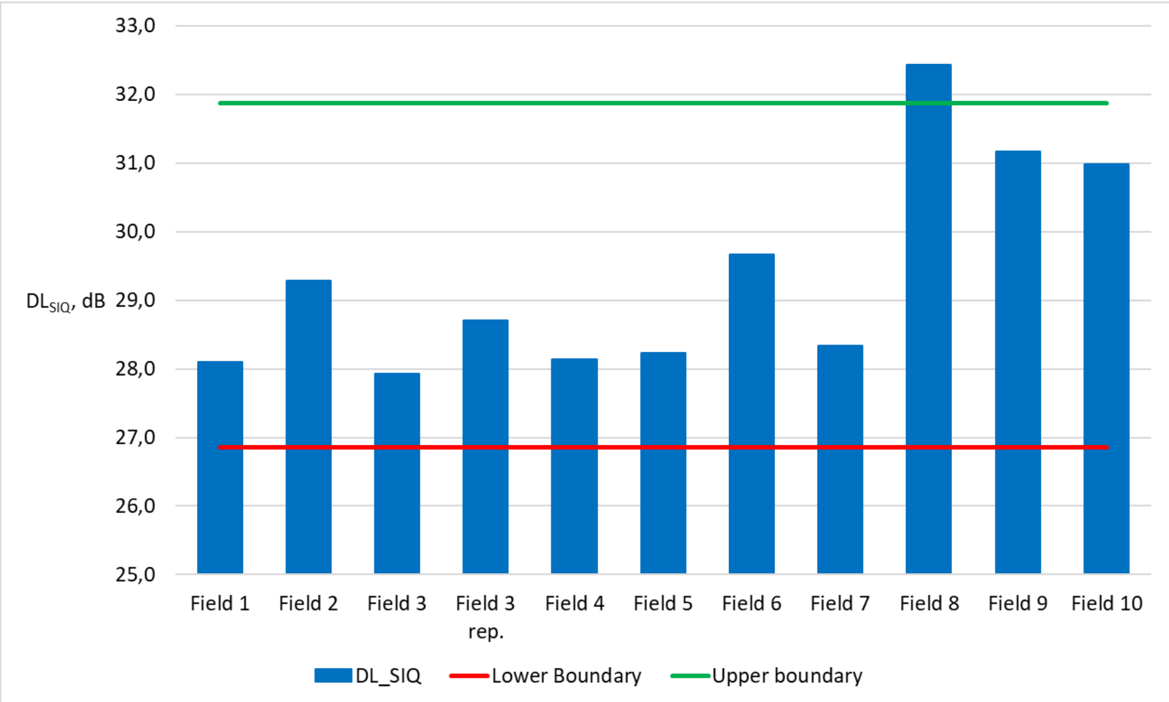


Figure 44. Differences of the single-number ratings of the individual SI_Q measurements on 10 different fields (+ 1 repetition) from their average value. The lower and upper boundary lines are calculated as the mean ±1,645 times the standard deviation of the 11 measurements.

Figure 45. Pictures of some of the measured fields of the metal noise barrier under test. View from the receiver side, opposed to traffic.

The lower and upper boundary lines in Figure 44 are a first attempt to establish an acceptance criterion. The mean value of the single-number rating is 29,4 dB, with a standard deviation of 1,5 dB. As a reasonable guess, one could assume that some variability is acceptable, but not below the lower boundary line, corresponding to the statistical average of the measured values minus 1,645 times the standard deviation (i.e. 26,9 dB). In principle, this criterion would reject the worst 5% of the fields. Actually, in the measured sample of 11 items, it would not reject any field.

5.2. Timber noise barriers

5.2.1. The noise barrier under test

The noise barrier under test consists of (see Figure 46):

- a porous concrete curb from zero to 0,50 m above the ground;
- wood panels with the street side face sound-absorbing and the external side face in wooden matchboard from 0,50 m to 3,50 m above the ground.

The wooden panels have a length of 2,60 m and a height of 1,00 m. The panels are inserted into HEA 180 posts spaced 2,67 m apart. The overall height of the barrier is 3,50 m. Each wooden panel is composed of a pine wood frame with beams and uprights at a distance of 0,605 m, to which a wooden panelling is fixed on the external side with self-tapping screws. On the street side, diagonal beams made of pine wood 50x25 mm are arranged, bevelled on two sides and fixed with self-tapping screws. The beams hold a black HDPE sheet against the frame. A sound-absorbing layer, 120 mm thick, made of thermoregulated synthetic fibres of recycled polyester with a density ≥ 30 kg / m^3 is placed in the gap between the rear matchboard and the HDPE sheet. The joints are sealed with an EPDM gasket.

The noise barrier is about seven years old.

Figure 46. View of the timber barrier under test from the side facing the traffic.

5.2.2. Quick sound reflection index measurements

In a half-day, eight quick reflection index tests and seven quick sound insulation tests have been done.

The quick reflection index tests have been done placing the linear antenna and the lightweight loudspeaker in eight different positions facing a field (post-to-post span) on the road traffic side of the noise barrier. One of these measurements was repeated three times for control. See Figure 48. Considering the results obtained on the metal noise barrier (see 5.1.2), the raw data have been processed, considering the four microphones from M2 to M5 (height above ground from 1,60 m to 2,80 m). The loudspeaker was at a height of 2,00 m above ground.

About one year before this test, a field of the same noise barrier was measured applying the full EN 1793-6 procedure with the standard equipment.

Figure 47. Microphone antenna, loudspeaker and control device in place for the quick sound reflection index measurements.

Figure 48 presents the results of all eight quick measurements, averaged over the **four microphones M2 to M5** (excluding the bottom microphone, M1, and the top microphone, M6), the results of a full EN 1793-5 test done about one year before and the tolerance interval defined by adding or subtracting to/from the EN 1793-5 measured value the measurement uncertainty at 95% confidence level. The general trend of the full EN measurement is captured even if with more peaks and valleys. In fact, for this lightly non-flat sample the quick method averages over 4 microphones, while the full EN method averages over 9 microphones and 3 grid positions (9x3 = 27 microphone positions). However, it is still true that for a noise barrier with an height in the range 4-5 m, when the antenna is simply placed on the ground, it is better to exclude the bottom microphone, too much influenced by the reflection of the sound waves emitted by the loudspeaker over the ground, and the top microphone, too much influenced by the sound waves emitted by the loudspeaker and diffracted back by the top edge to the microphone. If reputed useful for the particular composition of the barrier under test, the bottom microphone (M1) can still be used, knowing that the result could be interesting for a relative comparison of the different barrier fields, but cannot be compared with the full EN measurement.

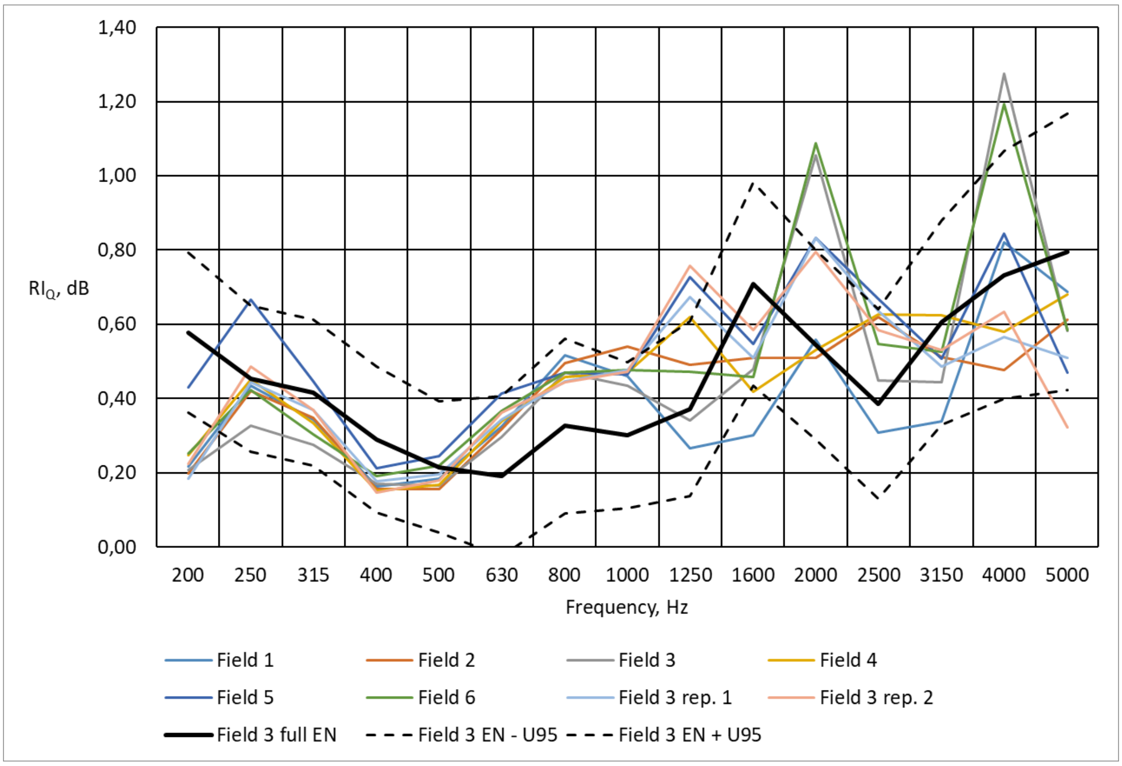


Figure 48. Colour lines: RI_Q spectra obtained with the quick method on the timber noise barrier for 8 different fields (1 repeated 3 times). Average over mic. M2-M5. Black continuous line: result of a previous EN 1793-5 measurement on a single field. Black dashed lines: EN 1793-5 measured value ± the expanded measurement uncertainty at 95% confidence level.

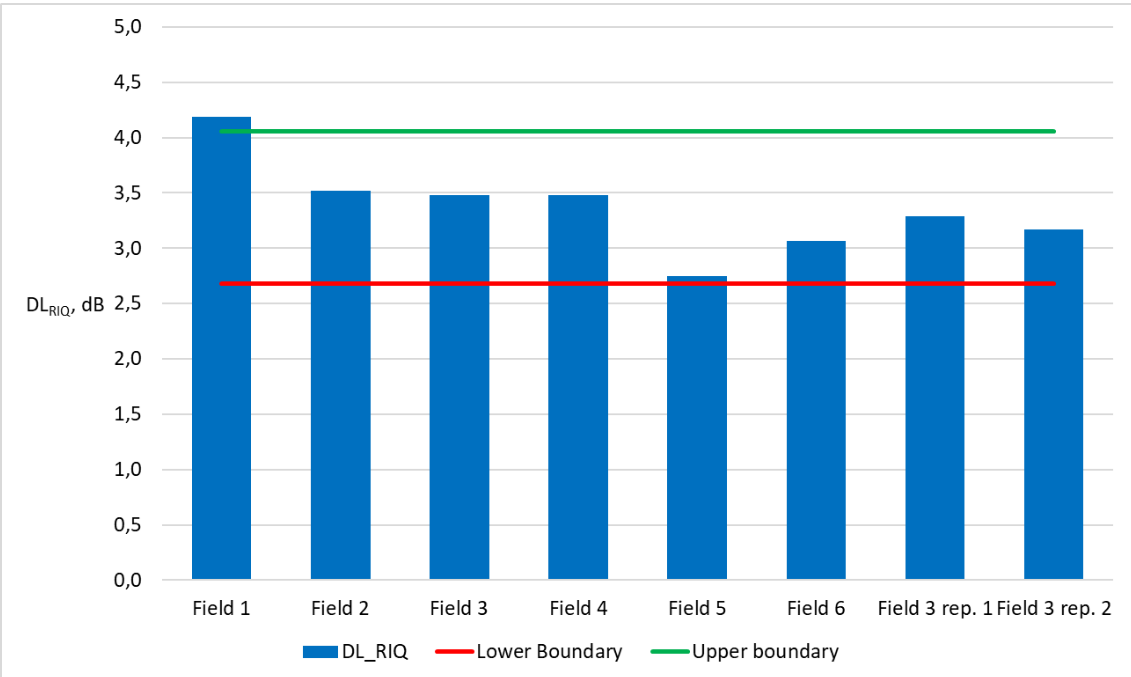


Figure 49. Differences of the single-number ratings of the individual RI_Q measurements on 8 different fields (1 repeated 3 times) from their average value. The lower and upper boundary lines are calculated as the mean ±1,645 times the standard deviation of the 8 measurements.

Figure 49 shows the differences of the single-number ratings of the individual RI_Q measurements on 8 different fields (1 repeated 3 times) from their mean value. The lower and upper boundary lines are calculated multiplying the standard deviation of the eight values by $\pm$1,645, which are the values of the abscissa of a standardized Gaussian distribution corresponding to a 90% coverage probability (bilateral).

This figure points out the actual differences existing among the different fields of a noise barrier in use where some minor defects begin to appear. Due to the combined variance of manufacturing, installation workmanship, etc., the single-number rating values range from 2,7 dB to 4,2 dB. Only a quick method, allowing to do multiple measurements in a short time, can give this information. A visual inspection cannot appreciate this variance: it would conclude that all fields are very similar and in good order and thus should get the same single-number rating. See Figure 50.

Figure 50. Pictures of some of the measured fields of the timber noise barrier under test.

The lower and upper boundary lines in Figure 49 are a first attempt to establish an acceptance criterion. The mean value of the single-number rating is 3,4 dB, with a standard deviation of 0,4 dB. As a reasonable guess, one could assume that some variability is acceptable, but not below the lower boundary line, corresponding to the statistical average of measured values minus 1,645 times the standard deviation (i.e. 2,7 dB). In principle, this criterion would reject the worst 5% of the fields. Actually, in the measured sample of 8 items, it would not reject any field, even if one of them got a single-number rating equal to the lower boundary (field n. 5).

5.2.3. Quick sound insulation index measurements

As previously said, in half-day eight quick reflection index tests and seven quick sound insulation tests have been done.

The quick sound insulation index tests have been done placing the linear antenna and the lightweight loudspeaker on the opposite sides of six different fields of the noise barrier; one measurement was repeated three times for control. See Figure 51 and Figure 52. Considering the results obtained on the metal noise barrier (see 5.1.3), the raw data have been processed, considering the four microphones from M2 to M5 (height above ground from 1,60 m to 2,80 m). The loudspeaker was at a height of 2,00 m above ground.

About one year before this test, a field of the same noise barrier was measured applying the full EN 1793-6 procedure with the standard equipment.

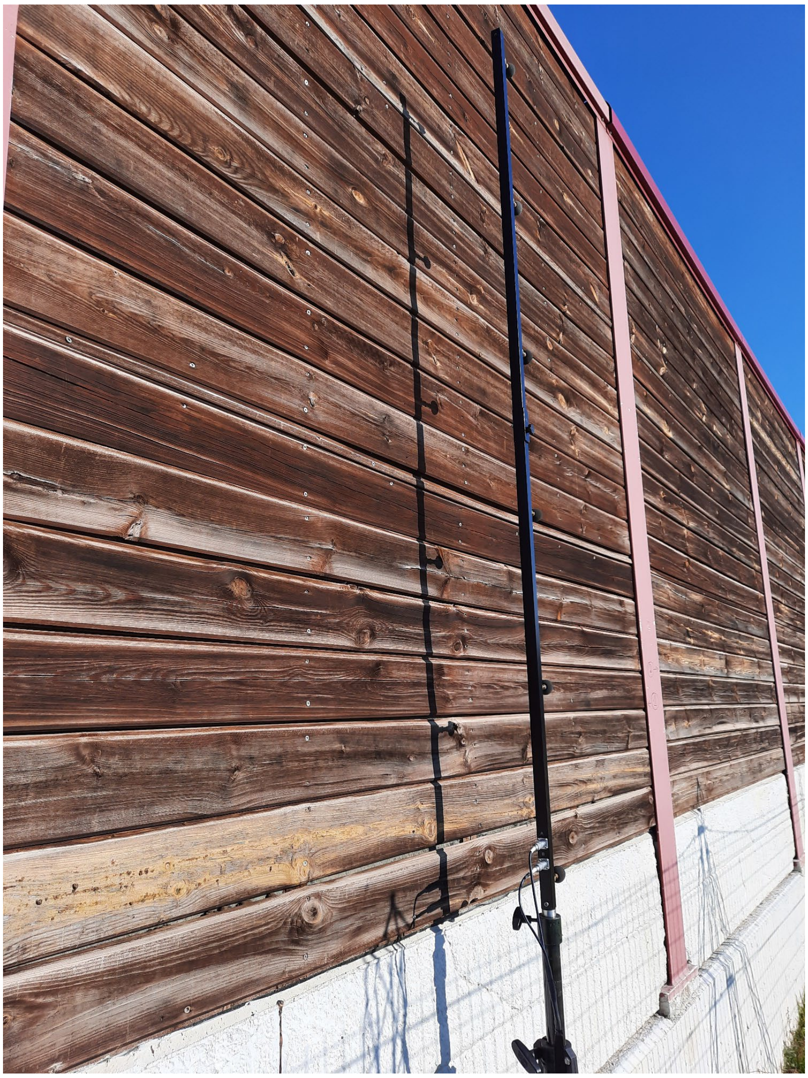


Figure 51. Microphone antenna in place for the quick sound insulation index measurements on the receiver side of the noise barrier.

Figure 52. Loudspeaker in place for the quick sound insulation index measurements on the traffic side of the noise barrier.

Figure 53 presents the results of all 7 quick measurements, averaged over the **four microphones M2 to M5** (excluding the bottom microphone, M1, and the top microphone, n. 6), the results of a full EN 1793-6 test done about one year before and the tolerance interval defined by adding or subtracting to/from the EN 1793-6 measured value the measurement uncertainty at 95% confidence level. The general trend of the full EN measurement is captured from the200 Hz to the 1600 Hz one-third octave bands. In the 2000 Hz to 4000 Hz bands the quick method trend is opposite to the full EN trend; however, the single-number ratings are quite similar: the difference between the average single-number rating of the quick method measurements and that of the full EN measurement is 1,4 dB, well inside the expanded uncertainty at 95% confidence level.

Figure 54 shows the differences of the single-number ratings of the individual SI_Q measurements on 7 different fields from their mean value. The lower and upper boundary lines are calculated multiplying the standard deviation of the 7 values by ±1,645, which are the values of the abscissa of a standardized Gaussian distribution corresponding to a 90% coverage probability (bilateral).

This figure points out the actual differences existing among the different fields of a noise barrier in use where some minor defects begin to appear. Due to the combined variance of manufacturing, installation workmanship, etc., the single-number rating values range from 11,6 dB to 14,8 dB. **Only a quick method, allowing to do multiple measurements in a short time, can give this information**. A visual inspection cannot appreciate this variance: it would conclude that all fields are very similar even if with minor defects and thus should get the same single-number rating. See Figure 55.

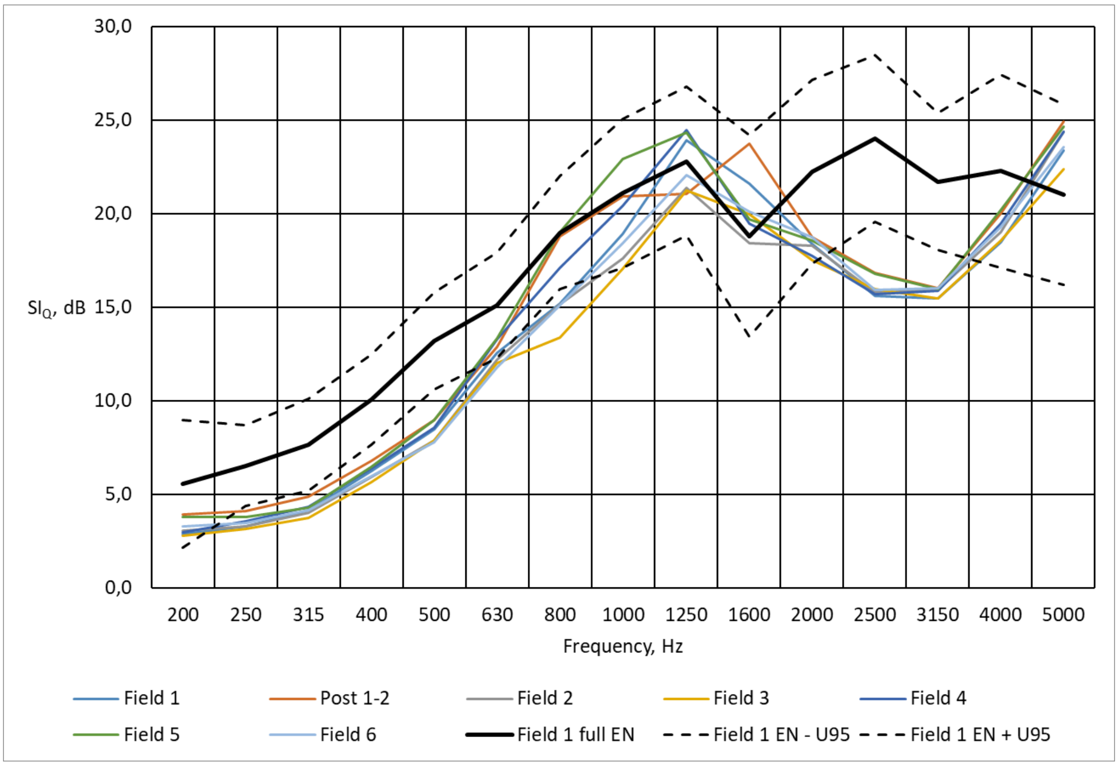


Figure 53. Colour lines: SI_Q spectra obtained with the quick method on the timber noise barrier for 7 different fields. Average over mic. M2-M5. Black continuous line: result of a previous EN 1793-6 measurement on a single field. Black dashed lines: EN 1793-6 measured value ± the expanded measurement uncertainty at 95% confidence level.

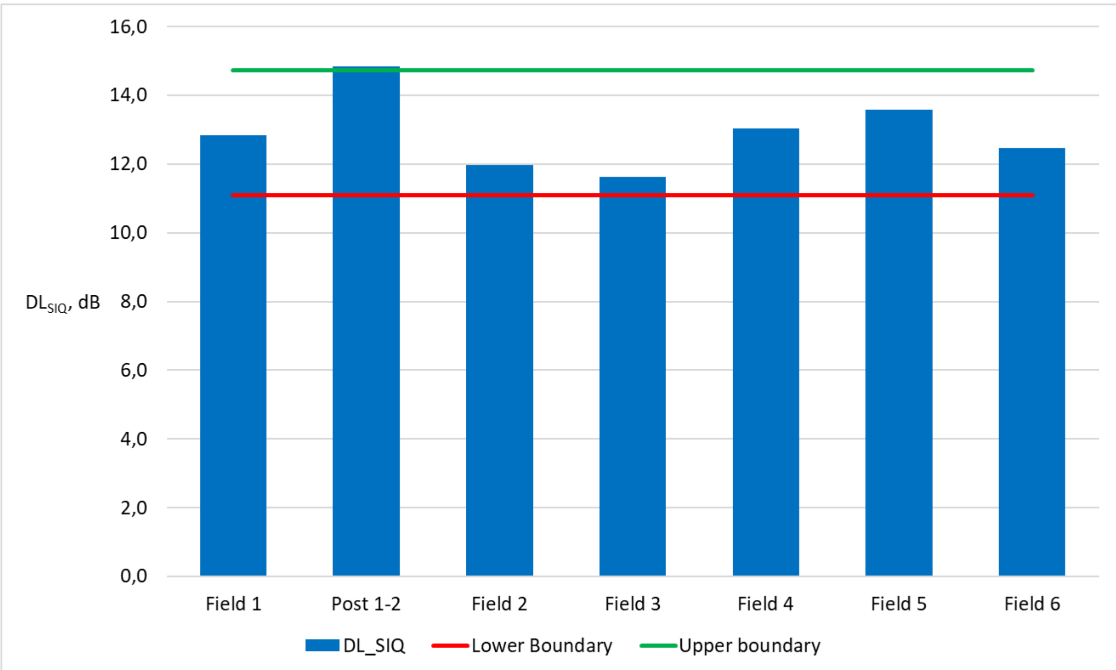


Figure 54. Differences of the single-number ratings of the individual SI_Q measurements on 7 different fields from their average value. The lower and upper boundary lines are calculated as the mean ±1,645 times the standard deviation of the 7 measurements.

Figure 55. Pictures of some of the measured fields of the timber noise barrier under test.

The lower and upper boundary lines Figure 54 are a first attempt to establish an acceptance criterion. The mean value of the single-number rating of the quick sound insulation is 12,9 dB, with a standard deviation of 1,1 dB. As a reasonable guess, one could assume that some variability is acceptable, but not below the lower boundary line, corresponding to the statistical average of measured values minus 1,645 times the standard deviation (i.e. 11,1 dB). In principle, this criterion would reject the worst 5% of the fields. Actually, in the measured sample of 7 items, it would not reject any field.

6. Laboratory tests at AIT

6.1 Introduction

This chapter reports the research activities performed by AIT on the validation of the new quick method (also called SOPRA in this document). The measurements were originally planned outdoors; nevertheless, because of the Austrian lockdown during November 2021 and other COVID-19 restrictions and the upcoming winter season, it was decided, with the PEB agreement, to perform the measurements in the laboratory.

The objective of the AIT measurement campaign was the comparison between the QUIESST methods (the well-known standards EN 1793-5 and EN 1793 -6, in their published version currently in force) and some possible variations of the SOPRANOISE quick method (SOPRA). Due to the ideal laboratory setup, it was possible to measure each test sample with the QUIESST method as well with the SOPRA method. For airborne sound insulation artificial defects were created in the noise barrier, to assess how well the methods can distinguish between "good" and "bad" noise barriers. For sound reflection/absorption two performant and one less performant aluminium noise barriers were tested and compared. This direct comparison between different methods on the same test sample implements a systematic way of assessing the characteristics of each measurement method and can be considered as complementary to the in-situ tests done by UNIBO reported in the preceding chapters.

6.1.1 Measurement methods used

The following measurement methods under direct sound field conditions have been considered in this research task:

- <u>QUIESST:</u> method according to EN 1793-5 for measuring sound absorption / reflection and EN 1793-6 for measuring airborne sound insulation.
- <u>SOPRA-6:</u> in this variation of the quick method (developed in SOPRANOISE) the full antenna is used: e.g., 6 microphones, from M1 to M6.
- <u>SOPRA-5</u>: in this variation of the quick method 5 microphones of the antenna are used: M1 to M5 (the top microphone M6 is excluded).
- <u>SOPRA-4</u>: in this variation of the quick method 4 microphones of the antenna are used: M2 to M5 (i.e., the bottom microphone M1 and the top microphone M6 are excluded).
- <u>SOPRA-3a</u>: in this variation 3 microphones of the antenna are used (e.g., M2, M3 and M4) having the same positions of the 3 central-column microphones of the QUIESST grid.
- <u>SOPRA-3b:</u> in this variation 3 microphones of the antenna are used (e.g., M1, M3 and M5, which have different positions than the 3 central-column microphones of the QUIESST grid.
- <u>SOPRA-1:</u> in this variation only 1 microphone of the antenna is used: M3, which is in front of the loudspeaker and equivalent to microphone n. 5 in the QUIESST grid.

In general, it should be noted that the window length of the Adrienne time window was always adapted to exclude any disturbing components possibly coming from the top edge or from the ground. This leads to small differences in the lowest reliable third-octave frequency band of the different microphones of the SOPRA antenna (especially for M1 and M6). In the calculation of the third-octave band values only the considered valid third-octave bands have been included.

6.2 Quick sound insulation index measurements

6.2.1 Measuring equipment used

Figure 56 and Figure 57 present respectively the linear microphone antenna on a supporting stand used for the measurements of airborne sound insulation (SOPRA method) and the microphone grid used for the measurements of airborne sound insulation according to EN 1793-6 (QUIESST method) in the AIT laboratory in Vienna. For the scope of this research only 6 microphones of the installed 16 have been used: these are labelled “M1” to “M6” from the bottom to the top, according to the setup used in the UNIBO measurements.

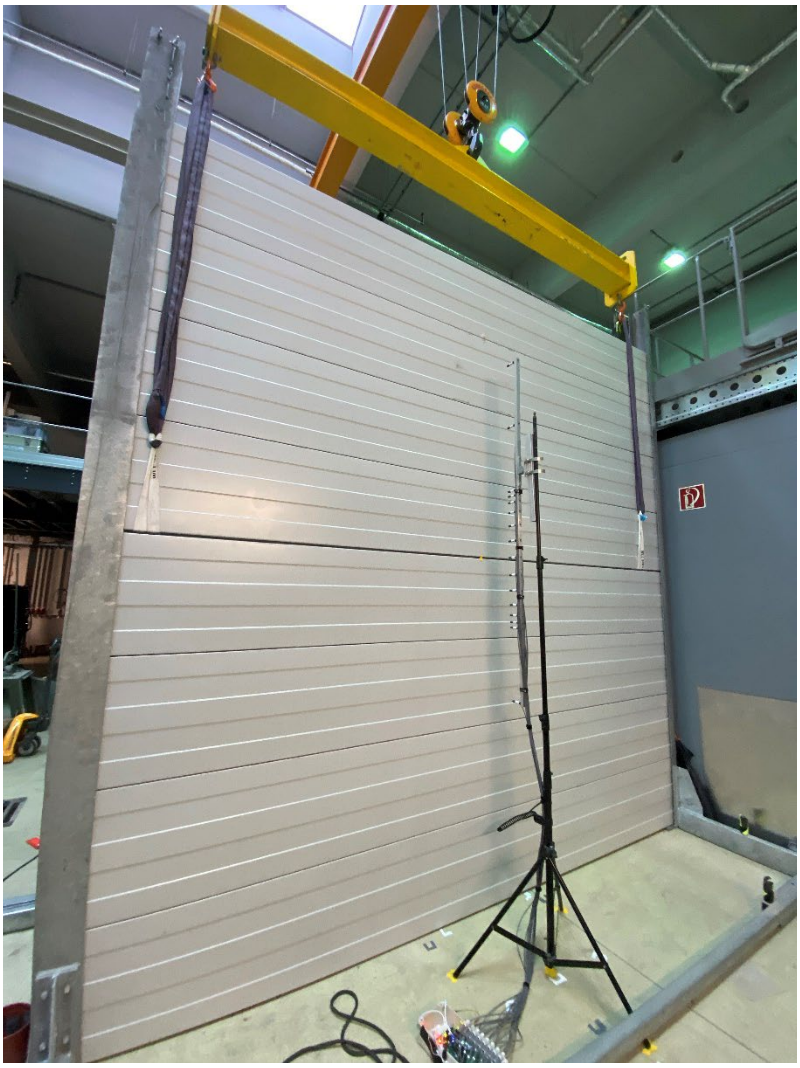


Figure 56. The linear microphone antenna on a supporting stand used for the measurements of airborne sound insulation in the AIT laboratory in Vienna. For the scope of this research only 6 microphones labelled “M1” to “M6” from the bottom to the top have been used (according to the setup used in the UNIBO measurements, see above).

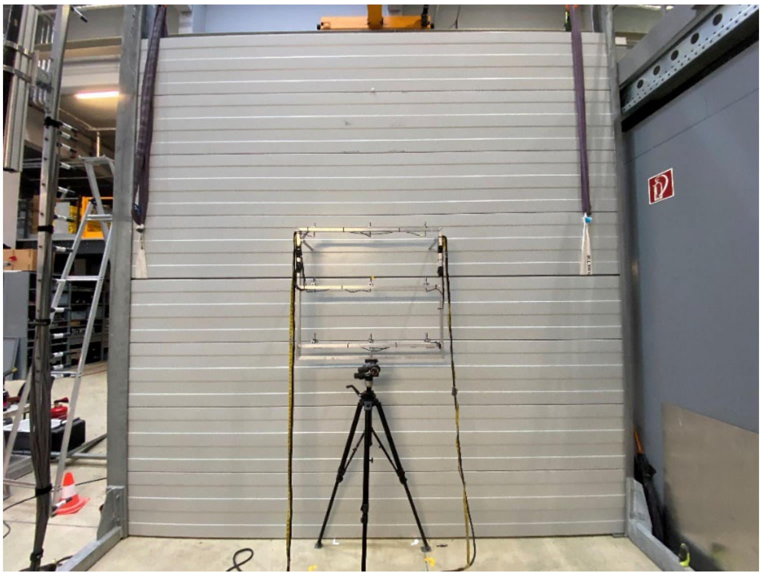


Figure 57. The microphone grid used for the measurements of airborne sound insulation according to EN 1793-6 (QUIESST method) in the AIT laboratory in Vienna.

6.2.2 Noise barrier under test and artificial defects

For the scope of this research several artificial defects have been created in the laboratory. The idea was to create an horizonal gap over the full length of the noise barrier field and to measure with all methods the resulting airborne sound insulation. Most noise barriers (especially in Austria) consist of vertically placed elements of 0,5 m to 2 m height stacked one over the other. For noise barriers with a concrete base layer, the sealing of the gap between the elements is the most important factor influencing airborne sound insulation at the acoustic element. Moreover, this experiment design was chosen, to reflect the increased vertical placement of microphones for the SOPRA method versus the QUIESST method. This must be considered in the comparison of the results.

The noise barrier under test is an aluminium barrier filled with absorptive material. The dimensions of the sample are 4 x 4 meters; the sample is made by 8 elements of 0,50 m height.

The loudspeaker-side (traffic side) of the barrier is perforated, while the backside of the barrier is fully reflective.

For the scope of this research the loudspeaker is placed in the middle of the barrier at a height of 2 m, and both the loudspeaker and the microphone antenna (for SOPRA) and /or the microphone grid (for QUIESST) stay fix, while the defect position was subsequently changed in the vertical direction.

The following **gap heights** (= vertical dimension of the gap) have been considered:

i. No gap at all: to be used as a reference
ii. 5 mm gap over the full length of the barrier
iii. 10 mm gap over the full length of the barrier
iv. 20 mm gap over the full length of the barrier
v. 50 mm gap over the full length of the barrier
vi. 100 mm over the full length of the barrier

It is also relevant to note, that due to the shape of the aluminium elements there was no view-through for 5 mm and for 10 mm gaps.

Regarding the position of the defects in the noise barrier, the following 4 **different positions** have been considered:

i. 200 cm from the ground, e.g., at mid-height of the barrier.
ii. 250 cm from the ground.
iii. 300 cm from the ground.
iv. 350 cm from the ground.

The number of the different combinations (5 gap heights x 4 positions x 2 methods + 2 references) leads to a total of 42 measurements: 21 measurements using QUIESST and 21 using SOPRA. Of course, the application of the different variation of the SOPRA methods have been performed during the post-processing phase, as the difference between the variants of the SOPRA method is in the selection of the microphones.

Figure 58 and Figure 59 show the 4 different gap positions used: at 200 cm, 250 cm, 300 cm and at 350 cm height to simulate different defect positions in the noise barrier under test, the AIT laboratory and some examples of the defects artificially created.

Figure 58. Different gap position used: at 200 cm height (top, left), at 250 cm height (top right) at 300 cm height (bottom left) and at 350 cm height (bottom right) to simulate different defect positions in the noise barrier under test.

Figure 59. The AIT laboratory and some examples of the artificial created gaps for simulating defects in the noise barrier under test.

6.2.3 Accuracy of SOPRA equipment vs QUIESST equipment

In a preliminary step the relative consistence of both measurement equipments is assessed. This is possible as three microphones of the quick linear antenna are theoretically in the same position of the QUIESST grid and, if the quality of the quick measurement equipment is to be considered valid for measurements according to EN 1793-6, the two systems should lead to similar results under repeatability conditions.

Figure 60 presents the correlation between single-number results considering the 3 centre-column microphones of the QUIESST grid (M2, M5, M8) and SOPRA-3a method (M2, M3, M4), which have exactly the same position. The dots represent the 21 different measurements performed on the noise barrier tested for both methods. A very high correlation confirms the high precision of the equipment used with deviations less than 0,5 dB.

Figure 61 shows the comparison between spectral results considering the 3 centre-column microphones of the QUIESST grid (M2, M5, M8) and SOPRA-3a method (M2, M3, M4), which have exactly the same position. The comparison is shown only for the following gap dimensions: no gap, 5 mm gap, 10 mm gap and 100 mm gap, at a height of 200 cm above ground. The vertical bars represent the uncertainty U_{95} according to EN 1793-6 and is plotted as an additional information. It should be noted that the uncertainty U_{95} according to EN 1793-6 is related to the average of 9 microphones, while here only the average of 3 microphones is shown.

These results confirm the very good accordance between both equipment and show the validity of using the hardware of the quick measurement system to assess the performance of a noise barrier.

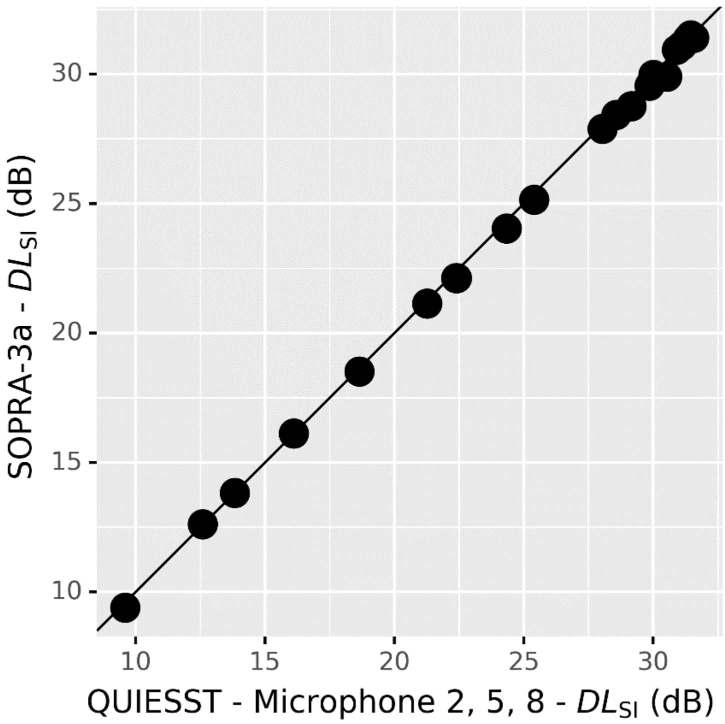


Figure 60. Correlation between single-number ratings of airborne sound insulation considering the 3 centre-column microphones of the QUIESST grid (M2, M5, M8) and SOPRA-3a method (M2, M3, M4), which have exactly the same position. The dots represent the different measurements performed.

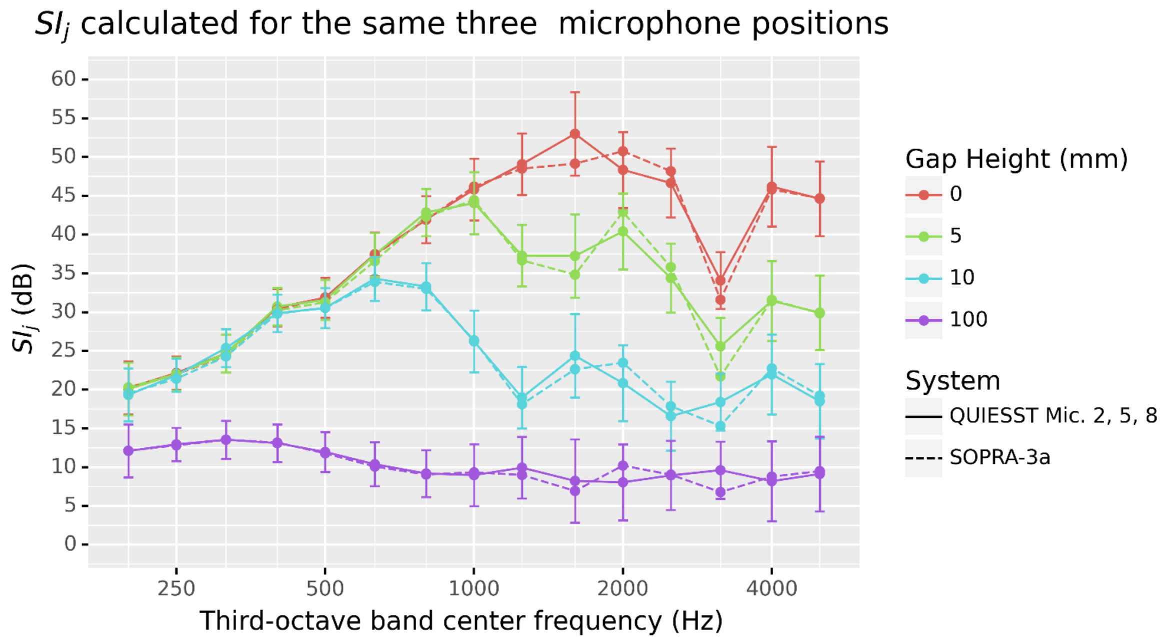


Figure 61. Comparison between spectral results considering the 3 centre-column microphones of the QUIESST grid (M2, M5, M8) and SOPRA-3a method (M2, M3, M4), which have exactly the same microphone position. The comparison is shown for the following gap dimensions: no gap, 5 mm gap, 10 mm gap and 100 mm gap. The vertical bars represent the uncertainty U_{95} according to EN 1793-6.

6.2.4 Results for airborne sound insulation

The results have been calculated according to the procedure explained in the EN 1793-6 and for every variation of the SOPRA method.

It should be noted that the window length of the Adrienne time window was adapted to exclude any disturbing components possibly coming from the top edge or from the ground. This leads to small differences in the minimum valid frequency of the different microphones of the SOPRA antenna (especially for M1 and M6).

Figure 62, Figure 63, Figure 64 and Figure 65 presents the results of the single number-rating for airborne sound insulation (DL_{SI}) using heat maps, where the results for every gap position, every gap height and every microphone positions are plotted as well as the average single-number rating over all microphones These figures give a very good overview of the results for the QUIESST method first, and then for SOPRA-6, SOPRA-5, SOPRA-4, SOPRA-3a, SOPRA-3b and SOPRA-1.

A gap is associated with a decrease of the airborne sound insulation from about 30 dB to 10 dB for the most extreme cases with a gap dimension of 100 mm at the height of the loudspeaker; as expected the effect increases with the gap dimension. Due to the energetic average one microphone with a low single-number rating will also lead to a low single-number rating in the average value over all microphones. For these horizontal defects the three rows of the QUIESST grid correlate very well with each other, but for a very high gap height (350 cm), the decrease in the DL_{SI} is marginal.

Here the SOPRA-6 method has a better sensitivity in detecting a horizontal gap - due also to the experiment design - as with 6 vertical microphones the defect can be pointed out at any height. The single-number rating for airborne sound insulation at microphone 6 decreases to a value of about 17 dB and clearly shows that there is something wrong with this (artificial defective) noise barrier. Nevertheless, it must be considered, that for vertical gaps not directly in front of the loudspeaker, the QUIESST grid will be more sensitive. It should be remarked that the window width for the signal coming from microphone M6 has been adjusted in order to exclude the diffracted wave from the top edge of the noise barrier, i.d. to avoid any edge effect. On the other hand, this implies shifting high the lowest reliable frequency.

With the exclusion of the top microphone from the average, the highest gap at 350 cm have little to no impact on the SOPRA-5, SOPRA-4, SOPRA-3a, SOPRA-3b and SOPRA-1 methods. As the relevant information of these measurements are focused from 200 cm onwards, the lowest microphone M1 carries no additional information in these measurement campaign. The position of the gaps was only placed from 200 cm above but the effect on the microphones should be considered symmetrical. Although, for the lower microphone the Adrienne time window must be shortened to suppress the ground reflection, the M1 might carry useful additional information for a defect at around 100 cm height. It can be estimated that for a gap at 100 cm above ground the value in the single-number rating for M1 would be comparable to the single-number rating for M5 at a gap position 300 cm. Nevertheless, for this (single-sided) set-up no relevant difference can be seen for SOPRA-4 and SOPRA-5.

The sensitivity of the method regarding the position of a defect and the vertical spread of the microphone can also be seen in the comparison between SOPRA-3a and SOPRA-3b, where the latter is more sensitive to the farther away gap positions. SOPRA-3a is naturally very comparable to QUIESST, as it includes the microphone positions also present in the QUIESST grid.

In SOPRA-1 only one microphone (in line with the loudspeaker horizontal axis) is used. Although some information is lost in comparison with the other methods, even one microphone can show the overall trend of the sound insulation. From these results the actual strength of an acoustic defect on a single microphone depending on the distance can be deduced. Of course a defect at the same height has the strongest effect, a defect 50 cm apart has still a significant (and comparable) effect. If the defect is more than 100 cm away, the influence of the defect is diminished and a defect at 150 cm distance has no influence at all, although from the geometric calculation a diffracted component might still be in the Adrienne time window.

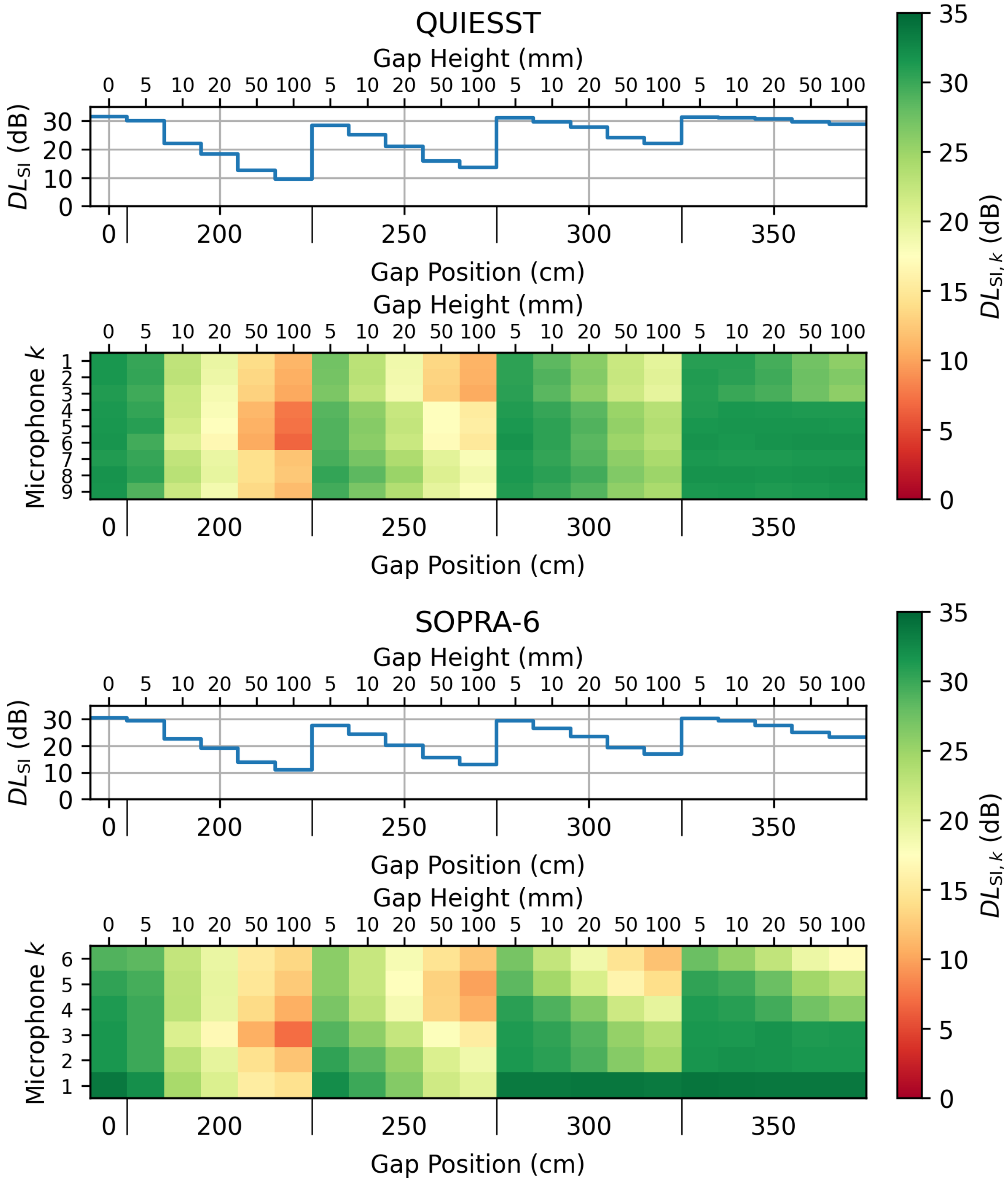


Figure 62. Heatmap of the single number-rating results (DLSI) for every gap position, gap height and every microphone for QUIESST (top) and SOPRA-6 (bottom).

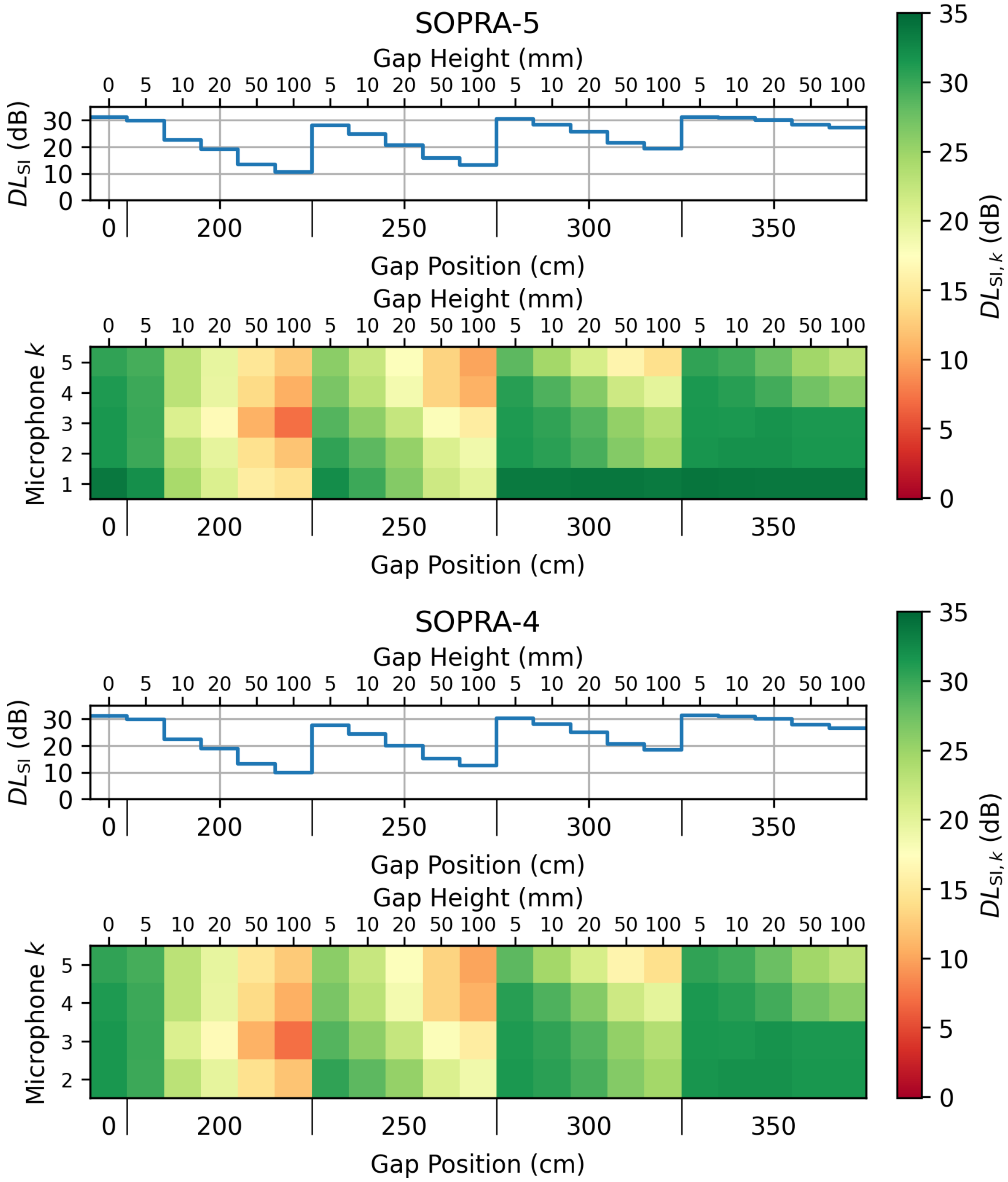


Figure 63. Heatmap of the single number-rating results (DLSI) for every gap position, gap height and every microphone for SOPRA-5 (top) and SOPRA-4 (bottom).

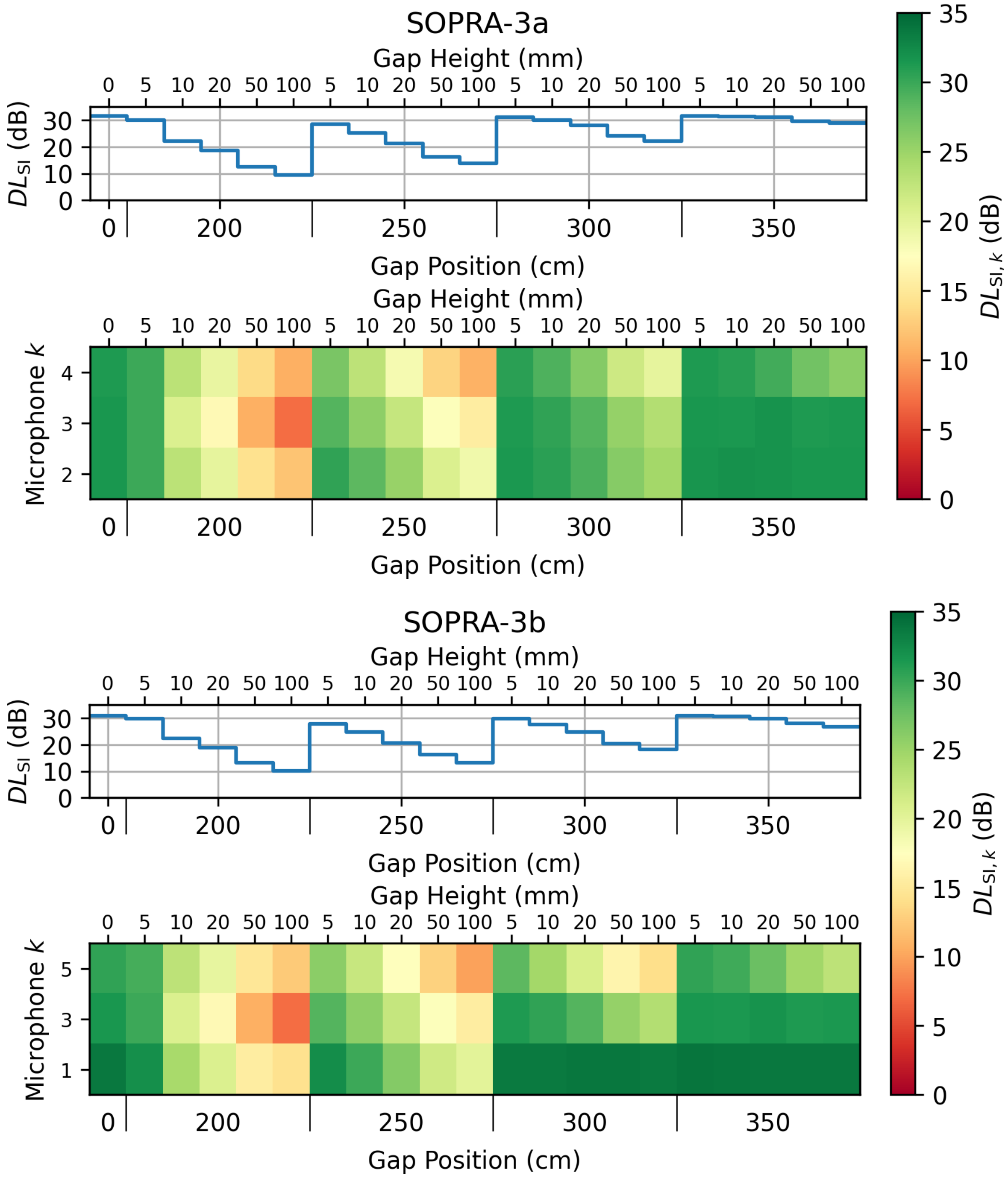


Figure 64. Heatmap of the single number-rating results (DLSI) for every gap position, gap height and every microphone for SOPRA-3a (top) and SOPRA-3b (bottom).

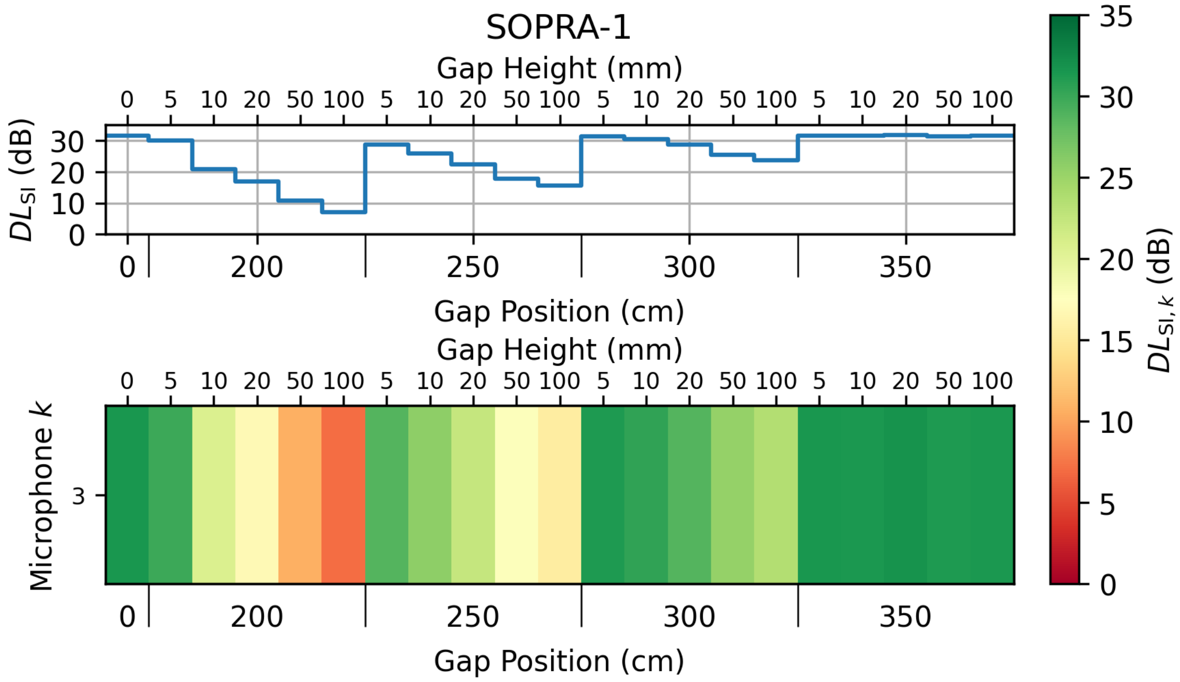


Figure 65. Heatmap of the single number-rating results (DLSI) for every gap position, gap height and every microphone for SOPRA-1.

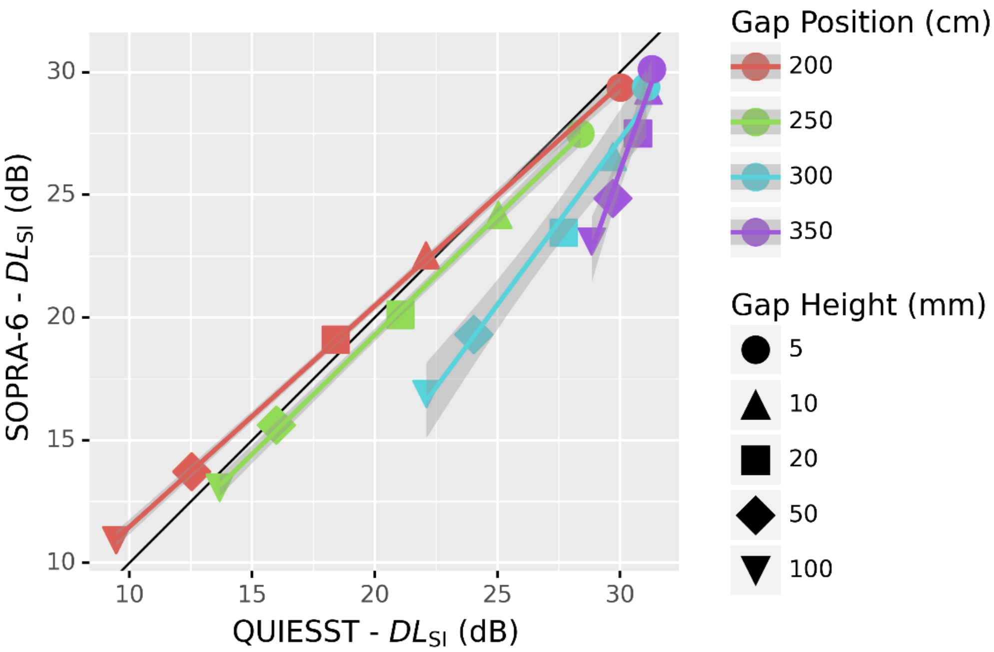
6.2.5 Correlations on airborne sound insulation

Figure 66, Figure 67 and Figure 68 illustrate the correlation between the single-number ratings of the results, DL_{SI}, between QUIESST and all analyzed variations of the SOPRA method considering each gap position separately. Different gap heights are denoted by different dot shapes, different gap positions are denoted by colors.

After a detailed analysis of the results the following considerations can be drawn:

- In general, the correlation between SOPRA and QUIESST is good, especially if every gap position is analysed separately.
- Gaps close to the QUIESST positions show very close results to each other (e.g., at 200 cm and 250 cm positions).
- For the higher gap positions (e.g., 300 cm and 350 cm positions) the difference in DL_{SI} values is significantly less in QUIESST than for SOPRA-6, SOPRA-5, -SOPRA-4 and SOPRA-3b. This is due to the lower sensitivity of the QUIESST method, but is not generally the case, as the experiment designs favours the SOPRA methods in this regard.
- The sequence of the DL_{SI}-values is still correct for every gap position for SOPRA-6, SOPRA-5, SOPRA-4, SOPRA-3a and SOPRA-3b.
- Even for SOPRA-1 (using only one microphone) the sequence of the DL_{SI}-values is still correct for most gap positions; only for the highest position (at 350 cm position) the values are not so representative.
- SOPRA-3a is a peculiar case, where all microphones of the antenna are in the same position as the 3 centre-column microphones of the QUIESST grid, and in this case the sequence is correct for every gap position and the correlation over all gap position is

nearly perfect. This is a situation similar to Figure 60, but here all microphones are used in the analysis for the QUIESST method.



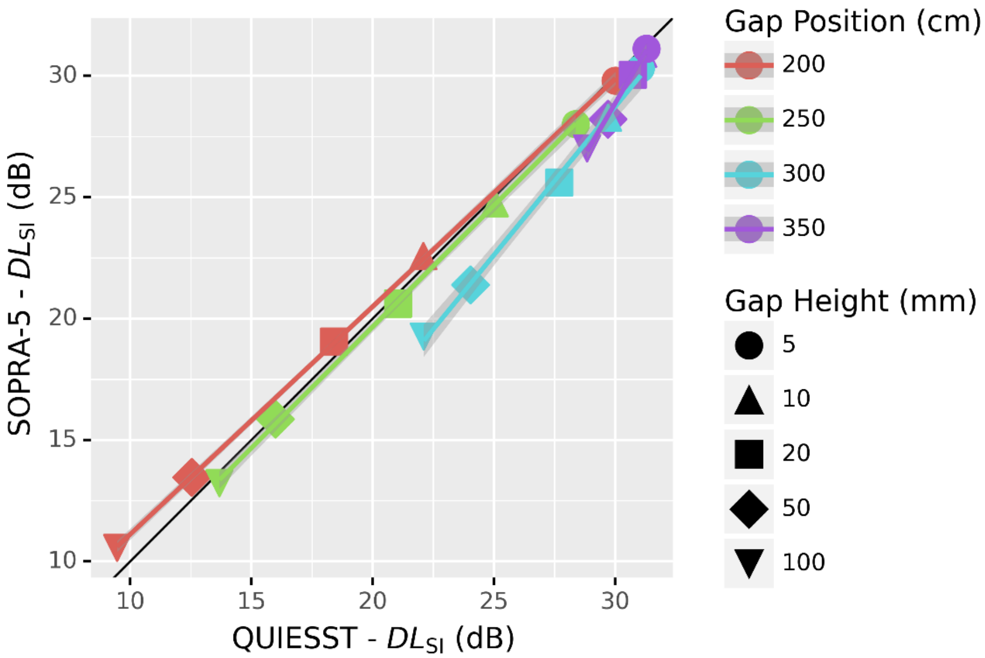


Figure 66. Correlation between single-number rating results (DLSI) considering each gap position separately, while different gap heights are denoted by different dot shapes, different gap positions are denoted by colours: QUIESST versus SOPRA-6 (top) and QUIESST vs. SOPRA-5 (bottom).

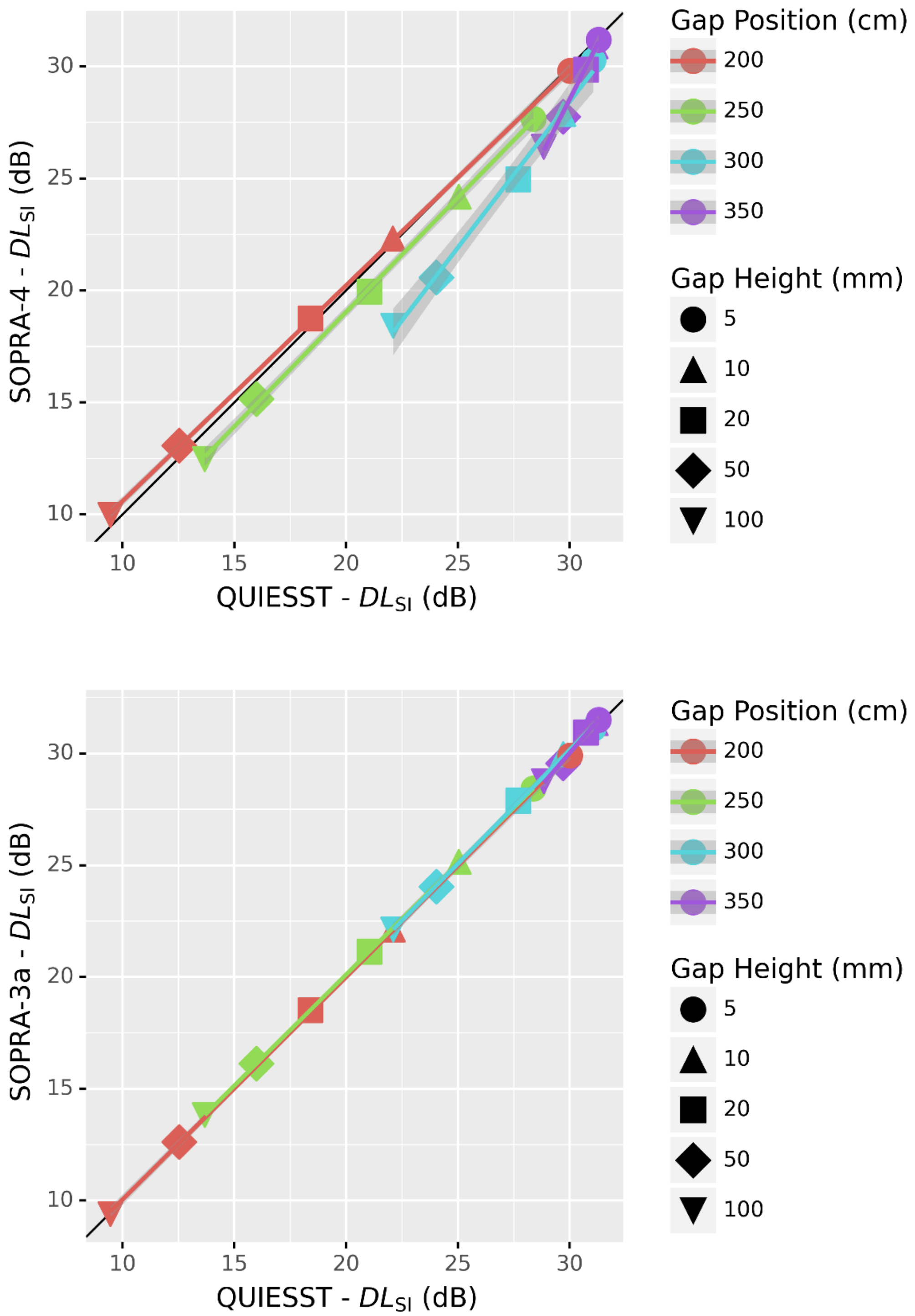
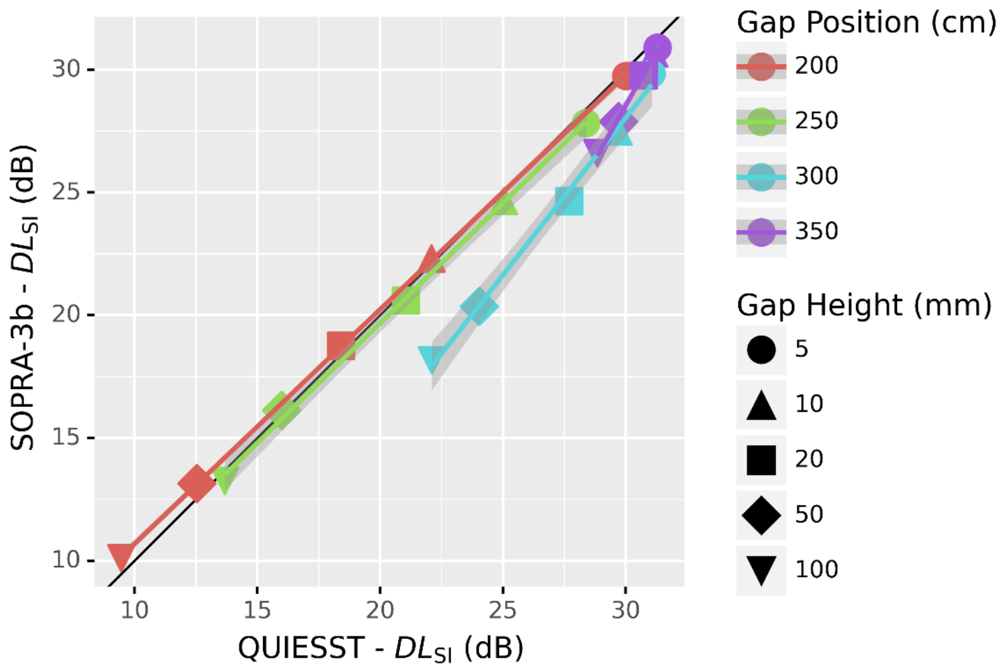


Figure 67. Correlation between single-number rating results (DLSI) considering each gap position separately, while different gap heights are denoted by different dot shapes, different gap positions are denoted by colours: QUIESST versus SOPRA-4 (top) and QUIESST vs. SOPRA-3a (bottom).



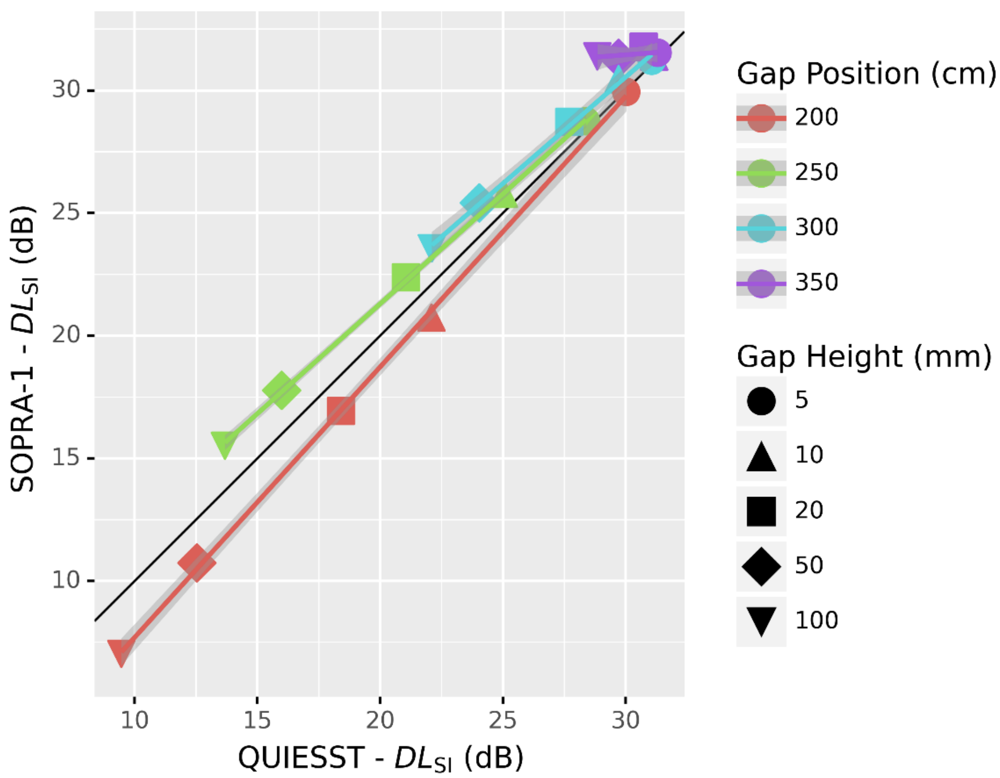


Figure 68. Correlation between single-number rating results (DLSI) considering each gap position separately, while different gap heights are denoted by different dot shapes, different gap positions are denoted by colours: QUIESST vs. SOPRA-3b (top) and QUIESST vs. SOPRA-1 (bottom).

6.2.6 Conclusion on airborne sound insulation

The measurement equipment used by AIT during this research for the quick method shows a very high correspondence with the full EN equipment: the deviations of parallel measurements are by far within the uncertainty U_{95} of the EN 1793-6 standard and this validates the SOPRA measurements performed for sound insulation.

A good accordance can be found for the sound insulation index DL_{SI} between QUIESST and all SOPRA methods: not surprisingly the best accordance was found between QUIESST and SOPRA-3a, which has the same microphone positions of the 3 centre-column microphones of the QUIESST grid.

SOPRA-6 seems to be more effective in finding defects, mainly because of the area covered from the microphones is more extended in the vertical direction; however, in order to avoid any influence on the top microphone (M6) of the diffracted sound on the top edge of the noise barrier (4 m high) the analysis window must be shortened, with a consequent shift to higher frequencies of the lowest reliable frequency. **SOPRA-5, SOPRA-4 and SOPRA-3b** seems to have a similar ability to find defects. Here it must be considered that the similarity between SOPRA-4 and SOPRA-5 is an artifact of an (asymmetrical) experiment design, where no defect is placed close to M1. Using less computation effort **SOPRA-3b** is as good in finding defects than **SOPRA-5**, as they have the same span in vertical direction and the interleaved microphones are not so relevant.

SOPRA-3a is very close to the QUIESST method, which is also due to the broad vertical gaps; this is just another confirmation of the precision of the new measurement equipment.

Nevertheless, **if the window length should be kept fixed,** as some ground reflections can reach M1 or diffracted components can reach M6, **SOPRA-4 seems to be the best compromise.**

SOPRA-1 still maintains the correct sequence of the defects for local defects but might imply an excessive reduction of the sampled area of the noise barrier.

6.3 Quick sound reflection index measurements

6.3.1 Measuring equipment used

The measurements of sound absorption / reflection index have been performed on the same noise barrier sample used for the measurements of sound insulation, which is a 4 x 4 m aluminium noise barrier, made of 8 cassettes filled with absorptive material; the cassettes are perforated only on the loudspeaker (road traffic) side.

Figure 69 and Figure 70 show respectively the microphone grid used for the measurements of sound absorption / reflection according to EN 1793-5 (QUIESST method), the lightweight loudspeaker Img Stageline PAB-305/SW and the linear microphone antenna used for the measurements of sound absorption / reflection in the AIT laboratory in Vienna. For the scope of this research only 6 microphones, labelled “M1” to “M6” from the bottom to the top, have been used (according to the setup used in the UNIBO measurements).

Figure 69. The microphone grid used for the measurements of sound absorption / reflection according to EN 1793-5 (QUIESST method) in the AIT laboratory in Vienna.

Figure 70. The lightweight loudspeaker Img Stageline PAB-305/SW and the linear microphone antenna used for the measurements of sound absorption / reflection in the AIT laboratory in Vienna. For the scope of this research only 6 microphones, labelled “M1” to “M6” from the bottom to the top, have been used (according to the setup used in the UNIBO measurements).

6.3.2 Accuracy of SOPRA equipment versus QUIESST equipment

In a preliminary step the relative consistence of both measurement equipments is assessed. This is possible as three microphones of the quick linear antenna are theoretically in the same position of the QUIESST grid and, if the quality of the quick measurement equipment is to be considered valid for measurements according to EN 1793-5, the two systems should lead to similar results under repeatability conditions.

Figure 71 presents the correlation between single-number results considering the 3 centre-column microphones of the QUIESST grid (M2, M5, M8) and SOPRA-3a method (M2, M3, M4), which have exactly the same positions. The dots represent different measurements performed on different test samples. A very high correlation confirms the high precision of the equipment used.

These results confirm the very good accordance between both equipment and show the validity of using the hardware of the quick measurement system to assess the performance of a noise barrier.

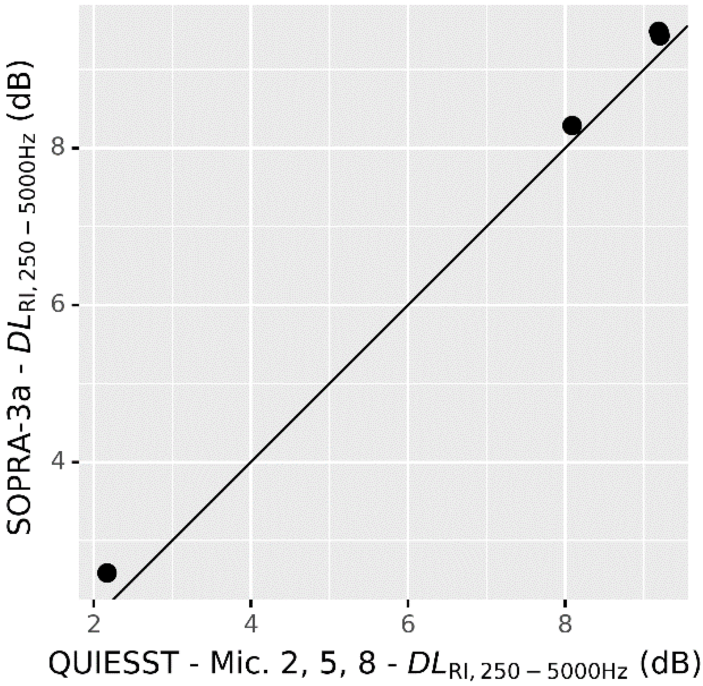


Figure 71. Correlation between single-number results considering the 3 centre-column microphones of the QUIESST grid (M2, M5, M8) and SOPRA-3a method (M2, M3, M4), which have exactly the same positions. The dots represent different measurement performed on different test samples.

6.3.3 Results for sound absorption / reflection

The results have been calculated according to the procedure explained in the EN 1793-5, simplified as described above for the quick method (see 4.2).

It should be noted that the window length of the Adrienne time window was adapted to exclude any disturbing components possibly coming from the top edge or from the ground. This leads to differences in the lower frequency limit of the different microphones of the SOPRA antenna (especially for M1 and M6).

Figure 72 shows the comparison between values of the single-number rating DL_{RI} for the QUIESST method and all variations of the SOPRA method applied in this research: SOPRA-6, SOPRA-5, SOPRA-4, SOPRA-3a, SOPRA-3b and SOPRA-1: all values are in a very small range, from 9.1 to 10.0 dB.

Figure 73 presents the results of the reflection index *RI* for the QUIESST method and all variations of the SOPRA method applied in this research, compared to the standard uncertainty s_R of the QUIESST method according to EN 1793-5 (vertical bars). The results of the SOPRA method are in very good accordance with those of the EN 1793-5 and by far within the uncertainty of the method, although it must be considered that the measurement uncertainty is defined for the average of the 9 QUIESST microphone positions. Only for few frequency bands (315 Hz, 630 Hz and 5 kHz) small divergences are present. As these are not the most relevant third-octave bands in the traffic noise spectrum, only small differences in the single-number ratings occur. Nevertheless, for the measured homogenous and flat noise barrier the differences are well within the uncertainty of the method.

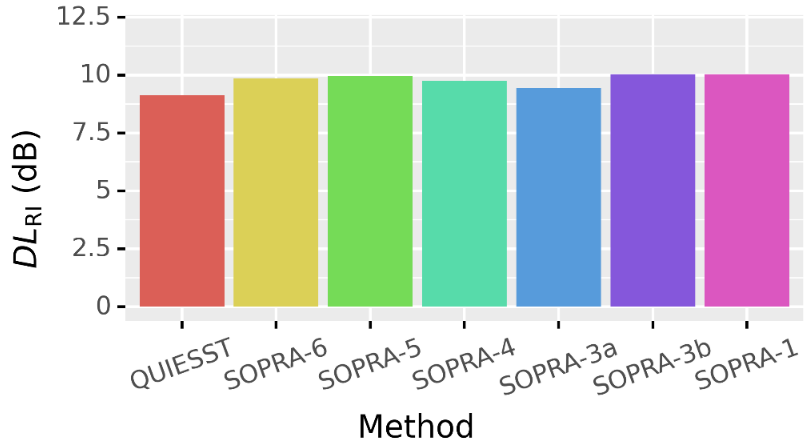


Figure 72. Single-number rating, DL_{RI}, for QUIESST method and all variations of the SOPRA method applied in this research.

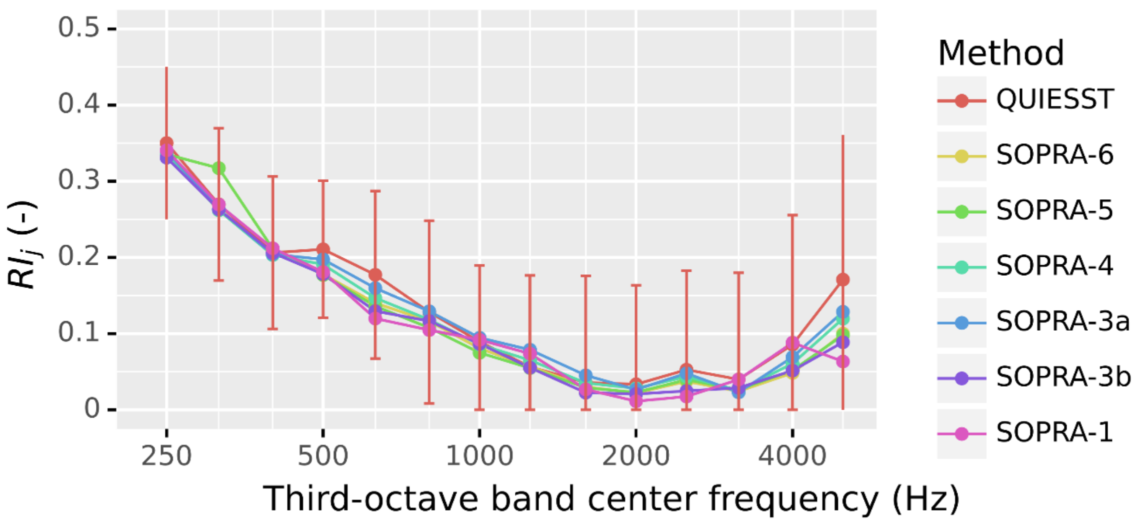


Figure 73. Reflection Index *RI* values for QUIESST method and all variations of the SOPRA method applied in this research, compared to the standard uncertainty s_R of the QUIESST method according to EN 1793-5 (vertical bars).

6.3.4 Conclusion on sound absorption / reflection

The measurement equipment used by AIT during this research confirms the very high precision found for the equipment used for measuring sound absorption / reflection. The precision of the equipment is by far within the standard uncertainty s_R of the standard EN 1793-5 and this validates the measurements performed for sound absorption / reflection.

A good accordance can be found for the single-number rating of the sound reflection index DL_{RI} between QUIESST and all SOPRA methods, in particular the **best accordance was found between QUIESST and SOPRA-3a** (which has the same microphone position of the 3 centre-column microphones of the QUIESST grid).

Slightly higher values can be found for SOPRA-6, SOPRA-5, SOPRA-4 and SOPRA-3b (even if this difference is no more than 1 dB for a very absorptive noise barrier).

It is also very promising that even the results according to SOPRA-1, where only a single microphone in front of the loudspeaker is used, has a similar value than QUIESST.

7. Recommendations for proper use

7.1 Reporting scheme (outline)

Table 7 presents a summary of the sound reflection results obtained on the metal noise barrier tested in-situ by UNIBO. This table, to be considered as an example, is the outline of a possible reporting scheme of the results of an extensive check carried out using the quick method on an installed noise barrier.

Table 7: Sound reflection results obtained on the metal noise barrier by UNIBO.

Noise barrier field n.	Single-number rating of sound reflection, DL_{RIQ} in dB
1	6,9
2	7,2
3	7,9
4	9,1
5	8,1
6	9,1
7	10,7
8	8,9
9	8,5
10	10,0
11	10,7
12	11,6
13	10,5
14	11,0
15	10,7
16	11,4
17	11,4
18	11,5
19	12,0
20	8,1
21	9,3
22	8,6
Mean	9,7
Standard deviation	1,6

7.2 Provisional acceptance criterion

After a quick method measurement campaign, enough data are collected to draw provisional conclusions on the quality of the performance of a noise barrier and on its variance along the installed fields. A threshold could be established for discriminating between “acceptable” and “non acceptable” noise barrier fields at a provisional level. Then some “non-acceptable” fields could be selected for further verification with full EN 1793-5 and EN 1793-6 tests, in order to decide on the definitive acceptability according to a specified limit value. In fact, only a standardized measurement, fully complying with European standards, has to be used to verify the conformity to a given specification.

Nevertheless, a provisional criterion, here called for the sake of simplicity “acceptance criterion”, is very useful to point out the less performing fields. It is entirely based on the values measured with the quick method.

In order to show how an acceptance criterion can be based on these data, it is necessary to consider the coverage factor *k* for a Gaussian distribution at a given cumulative probability, see Table 8. The complement to 100% of the cumulative probability is the probability to reject a given field.

Table 8: Coverage factor *k* as a function of the cumulative probability of a standardized Gaussian distribution *N*(0,1).

Monolateral probability	***k***	***Rejection probability***
84,0%	0,994	16%
90,0%	1,282	10%
95,0%	1,645	5%
97,5%	1,960	2,5%

Each single field of the tested noise barrier can be checked for acceptance comparing the single-number rating measured with the quick method on this field and the value given by the mean value over all fields ± the coverage factor times the standard deviation over all fields. Using the latter product with the minus sign defines a lower boundary of a tolerance interval:

$$DL_{RIQ,i} \geq \overline{DL_{RIQ}} - k \cdot s\left(DL_{RIQ}\right) = Lower\ Boundary \tag{6}$$

The lower boundary (red line) in Figure 37 and Figure 49 is calculated using this criterion for a 95% cumulative probability (*k* = 1,645). This means that on average 95% of the tested fields should fall inside the acceptance interval, while 5% of them are “rejected” (in a statistical sense and provisionally). In fact, the field n. 1 in Figure 37 is below the acceptance value and is rejected.

The road authority can select the confidence level it wants to define the lower limit of acceptance. The smaller the value of *k*, the stricter the acceptance criterion. For example, selecting *k* = 1,282 (monolateral probability of acceptance 90%) the lower boundary of acceptance becomes 7,7 dB and also the second field in Table 7 is rejected.

The same line of reasoning can be applied for airborne sound insulation (see Figure 44 and Figure 54).

7.3 Sampling criteria for representativeness of the sample

The above acceptance criterion is applied on the full set of single-number ratings constituting a representative sample gathered with quick measurements. However, when in-situ it should be decided whether the acquired sample is representative or not before applying any selection criterion on it. The criterion for deciding when a sample is representative, in a statistical sense, is called here “sampling criterion”.

If it is desired to get a representative sample without having to test all or most part of the noise barrier, then it is possible to use a statistical approach similar to those explained above to decide to stop sampling. Alternatively, it can be decided to have in all cases an extensive sampling of the noise barrier fields. An outline of these sampling procedures is given below following the two different lines of reasoning, called here sampling criterion A and sampling criterion B.

7.3.1 Sampling criterion A

The rationale of this criterion is to avoid an excessive number of measurements, i.e. avoiding to waste time in a useless oversampling that does not give more information. It works as follows.

1. Take a minimum sample of quick measurements (e.g. $n \geq 10$) and calculate the single-number ratings in real time:

$$\left\{DL_{RIQ,1}, DL_{RIQ,2}, .., DL_{RIQ,n}\right\} \tag{7}$$

2. Compare the difference between maximum and minimum value in this sample with the sample standard deviation s times a given safety factor k:

$$\max\left(DL_{RIQ,i}\right) - \min\left(DL_{RIQ,i}\right) \leq k \cdot s \ \ (i = 1, \dots, n) \tag{8}$$

3. If the condition (8) above is satisfied for all measured values ($i = 1, \dots, n$), then the sample is judged representative, otherwise more measurements shall be taken (not less than 3) in order to increase the sample and step 2 shall be repeated.

The safety factor k is extracted from a standardized Gaussian distribution, i.e. one can refer again to Table 8.

7.3.2 Sampling criterion B

However, a different approach can be adopted, borrowing from that in use in Austria. The rationale of this criterion is to have an extensive sampling of the noise barrier fields. Actually, two different criteria are applied, one for sound absorption/reflection and one for sound insulation.

<u>Sound absorption/reflection</u>

1. If the noise barrier is no more than 1 km long, then at least 75% of the total length of the noise barrier (l_g) should be measured (which is the sampled length l_s). This should be equally distributed over the whole noise barrier. When the total length of the noise barrier

is greater than 1 km, then 1 km plus an additional length should be tested, according to formula (9). See also Figure 74.

$$l_s \geq \begin{cases} 0{,}75 \cdot l_g & l_g \leq 1\ km \\ 0{,}75 \cdot \left[1 + \ln(l_g)\right] & l_g \geq 1\ km \end{cases} \tag{9}$$

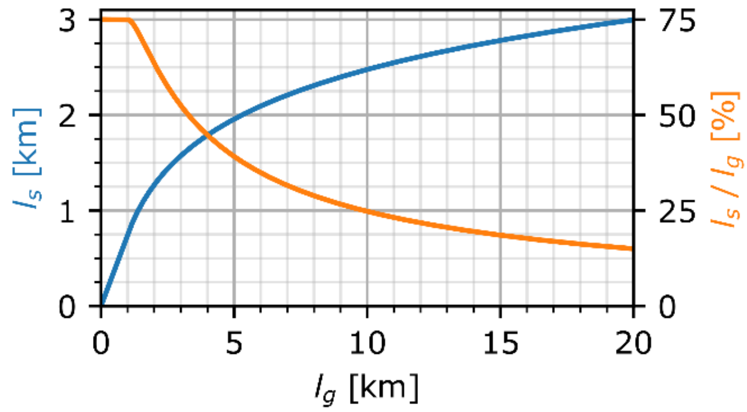


Figure 74. Length of the sample against the total length of the noise barrier under test.

2. From the single-number ratings of the quick measurements, the noise barrier fields which represent the 10%, 20% and 50% quantiles are selected.
3. The 3 identified fields will be measured according to EN 1793-5.
4. Then another criterion for acceptance/rejection can be applied to the full EN 1793-5 measurements; it shall be in accordance with GUM. This criterion is NOT part of the sampling procedure; it is part of the decision process instead, which is up to the road authority.

<u>Sound insulation</u>

1. The visual inspection procedure developed in WP3 is applied (see [12]). As a result, the noise barrier fields are subdivided in the following 4 classes:
   a) No visible defects
   b) No view through the noise barrier (can be “green”, yellow” or “red” according to the inspection procedure [12])
   c) View through the noise barrier (but categorized as “green” according to the inspection procedure [12])
   d) View through the noise barrier (and categorized as “yellow” or “red” according to the inspection procedure [12])
2. Noise barrier fields in class d) are considered defective and are not measured.
3. For each class a), b) and c) at least 10% of the noise barrier fields are selected and measured applying the quick method. The selection can be based on defects at the acoustic element as well as at the post. For each selected field the acoustic element as well as the

adjacent right post is measured with the quick method. They shall be uniformly distributed along the noise barrier.

4. For noise barrier no more than 1 km long, the three noise barrier fields corresponding to the following quantiles will be measured according to EN 1793-6: 10%, 20%, 50% (based on a combined distribution of element and post quick measurements).
5. For every additional km after the first, one additional field will be measured, selected in the quantile range between 5% and 25%. These additional fields should be equally distributed on the whole noise barrier.
6. The identified fields shall be measured according to EN 1793-6 both at the element and the post; if the selection was driven by the element, then the acoustic element and the right post shall be measured; if the selection was driven by the post, then the post and the left element shall be measured.
7. Then another criterion for acceptance/rejection can be applied to the full EN 1793-6 measurements; it shall be in accordance with GUM. This criterion is NOT part of the sampling procedure; it is part of the decision process instead, which is up to the road authority.

8. Conclusion and outlook

The work presented in this report concludes the WP4 of the SOPRANOISE project. In brief, the following conclusions can be drawn.

- SOPRANOISE proposes a 3-step progressive approach.
- Step 1 of SOPRANOISE 3-step approach is a *qualitative* visual/aural inspection of a noise barrier, to be carried out in situ. This **in-situ inspection can spot visible defects but cannot find hidden defects**, e.g. a lack of material inside an acoustic panel; thus, a qualitative in-situ inspection can conclude that a noise barrier is **not** acceptable because it has visible defects, but it cannot conclude that a noise barrier is acceptable (for example a lack of material inside a composite panel may be a reason for both a reduced sound absorption and a reduced sound insulation). Therefore step 2 is needed, i.e. a quick measurement method, capable of giving *quantitative* results.
- Such quick method should allow to test in a relatively short time the acoustic performance of a representative sample of noise barrier fields, which is not possible applying the full method standardized in EN 1793-5 and EN 1793-6, because of the complexity of the method. However, the **full EN tests are mandatory for assessing the compliance of the noise barrier to the specifications** (step 3 of the SOPRANOISE approach).
- **It is possible to conceive and implement a quick method for sound reflection/absorption and sound insulation that gives results close to the full EN 1793-5 and EN 1793-6 method (QUIESST method) while being considerably faster to apply** (step 2 of the SOPRANOISE approach).
- The new quick method, also called SOPRA method, has been designed and implemented by UNIBO and AIT in the frame of the SOPRANOISE project, WP4.
- UNIBO and AIT have built a portable prototype equipment, lightweight, battery operated and easy to handle.
- The measuring equipment built by UNIBO and AIT are based on different yet similar hardware components available on the market with a moderate overall cost (see Figure 2 and Figure 15).
- The measurement and post-processing software already developed at UNIBO and AIT for the full EN method has been simplified and transferred to the new portable equipment.
- The working frequency range of the quick method is 200 – 5k Hz in one-third octave bands, the same as EN 1793-5 and EN 1793-6.
- The quick method uses an MLS signal, which has the best immunity to background noise, essential for in-situ measurements.
- The quick method is largely automated: the operators have to place the loudspeaker and the microphones at prescribed distances from the noise barrier and push few buttons. Thus, the degree of expertise required to quick method operators is not so high as for applying the full EN 1793-5 and EN 1793-6 method.
- **The new portable prototype equipment has proved to work effectively on real noise barriers installed along the A22 motorway**, connecting Italy to Austria. See the quick measurements done by UNIBO (points 5.1 and 5.2). The results obtained, both for sound reflection and sound insulation are credible and close to those obtained o the same noise barriers applying the full EN 1793-5/6 procedure.
- In the laboratory tests done at AIT, **the new quick method demonstrated a very high correlation with full EN 1793-5 or EN 1793-6 results and a high repeatability** (see point 6 and see also Deliverable D4.1).

- An **acceptance criterion** for the individual quick measurements can be conceived relying on a statistical approach, it has been outlined in point 7.1.
- The assessment of the representativity of a sample of quick measurements (**sampling criterion**) clearly is something that goes beyond the SOPRANOISE project; however, two different approaches to this issue have been outlined in point 7.2.

The research on the above topics is going to continue after the end of the SOPRANOISE project. Both UNIBO and AIT are willing to investigate more on the acceptance criterion for the individual quick measurements and on the sampling criterion for the representativity of the sample of quick measurements. With the fading out of the pandemic, it is hoped that this research could be done in-situ along some motorways.

At the same time, the acquisition of many more data, which is possible with the new quick method, should allow to assess the in-situ repeatability of the quick method and its correlation with the full EN method.

In pursuing this goal, UNIBO and AIT will probably improve the equipment for the quick method, making it replicable in a relatively short time with off-the-shelf components available on the market.

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