Conférence Européenne des Directeurs des Routes

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CEDR TRANSNATIONAL ROAD RESEARCH PROGRAMME 2018

SOPRANOISE

D5.2 SOPRANOISE Final report
Guidelines for NB use and scientific report
April 07, 2022

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Introduction and structure of deliverable D5.2

The present document regroups the reports of the following 2 WP5 tasks that have been achieved:

- T5.4 How to assess the NB acoustic performances
- T5.5 Guidelines and the final scientific report

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SOPRANOISE

M5.4 Assessment of the intrinsic performances of installed Noise Barriers

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1 Introduction

Noise barriers (NB) are obstacles to *sound propagation* purposely built to shield receivers from excessive noise generated by road or railway traffic (Figure 1). Today, NB are considered the most effective noise mitigation measures available when targeting *high noise reductions*. For this reason, the more stringent the noise legislation across Europe becomes, the more NB are installed or refurbished along many road and railway corridors.

Figure 1: To reduce traffic noise, NB are placed as obstacles to the sound propagation [1]

Many factors need to be considered in the detailed design of NB. About their acoustic performance (which is the main reason for using them), the noise reduction achieved by NB in their environment is characterized by the “Insertion Loss” (IL: difference in sound level at a receiver location with and without the presence of the NB): this is an *extrinsic* characteristic that involves a lot of factors, all influencing the final NB effective performances. Specifically attached to *the product itself*, the *intrinsic* acoustic characteristics are: *sound absorption / reflection*, *airborne sound insulation* and *intrinsic sound diffraction*. To understand their roles, Figure 2 shows how physics rules the IL of a NB:

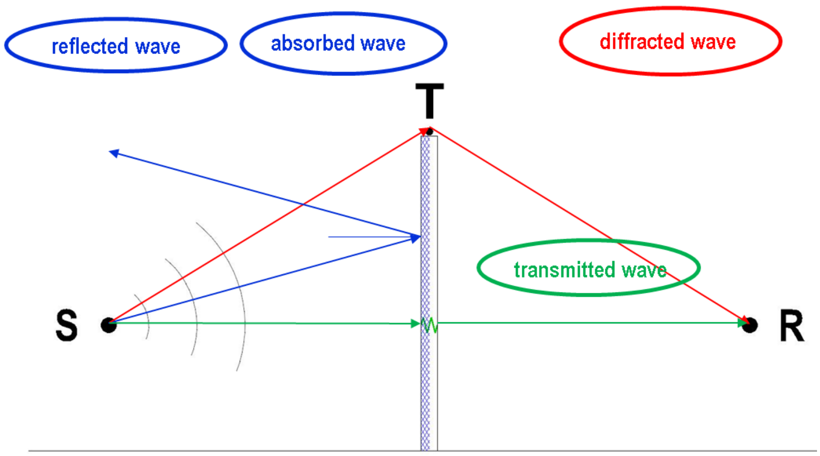


Figure 2: Sound reflection / absorption, sound transmission, sound diffraction [2]
S: *sound source* (e.g.: the vehicles); **T**: top of the NB, **R**: receiver (e.g.: a dwelling)

Reflections occur when a *sound wave* hits the exposed side of the NB : it partly reflects on it and this *reflected sound (wave)* can affect the facing areas; the (intrinsic) *sound absorption* performance of the barrier can usefully reduce reflections. **Transmission** occurs when a *sound wave* hits the exposed side of the NB: it partly transmits through the NB itself. As the main role of the NB is to play as an obstacle to the sound propagation, this transmitted energy must be negligible compared to that one diffracted at the top edge of the NB.

A NB should act as an obstacle to the sound propagation; however, a part of the *sound wave* still passes over it: this is called **diffraction**. The *sound wave* diffracts on the top edge of the NB (where it is partly attenuated), and then propagates to the protected side of the device.

This report relates to the assessment of the *intrinsic* performances of installed NB, whatever along roads or railways, with different methods: from the simplest up to the most detailed ones, each replying to relevant different uses.

2 The SOPRANOISE 3-step approach

To assess the *intrinsic* acoustic performances of installed noise barriers from the easiest (but less accurate) way up to the most accurate one (but obviously related to more effort and money), SOPRANOISE established an "engineering progressive approach" with the following 3 successive steps (see Figure 3) :

(1) in-situ inspections,

(2) in-situ "quick" tests[1],

(3) in-situ "full" tests[2],

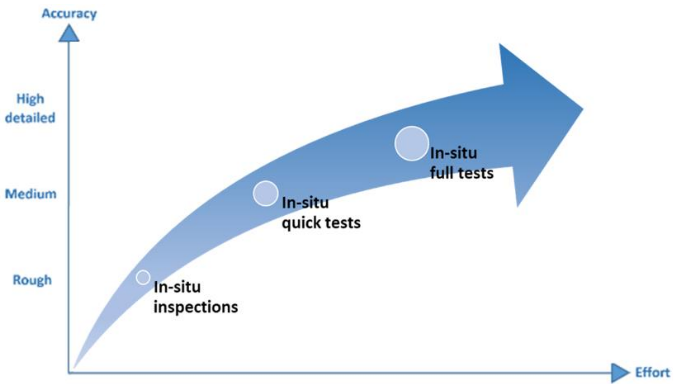


Figure 3: SOPRANOISE 3-steps approach to characterize the *intrinsic* acoustic characteristics of installed noise barriers: from less accurate but easy methods up to the more accurate full in-situ tests.

At the end of each step, relevant decisions should be taken whether fair conclusions could be drawn: "**acceptance**[3]" or "**rejection**", otherwise further tests are still necessary (see successive steps in Figure 4).

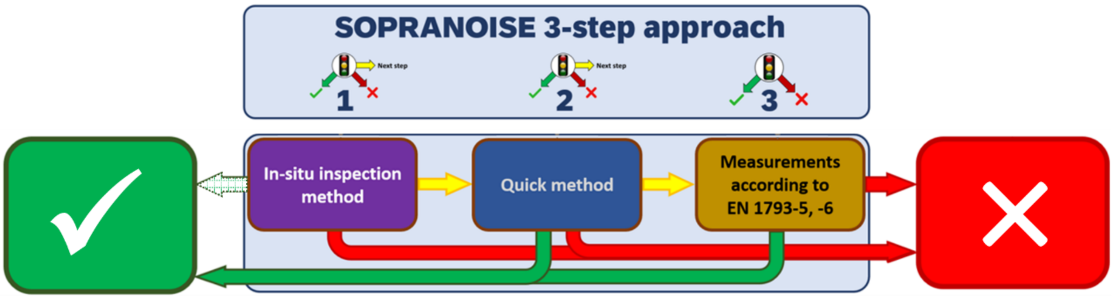


Figure 4: SOPRANOISE 3 successive steps approach to characterize the *intrinsic* acoustic characteristics of installed noise barriers: *main* principles (adapted in Figure 5 and Figure 6).

However, the validity of the conclusions may vary depending on what we want to do with the test results. In facts, we can have 2 main different kinds of assessment:

- **monitoring** the evolution of performances of already installed noise barriers (e.g.: along time, in regular intervals and/or before decommissioning stage) as an objective tool to take decisions on NB replacement);
- **approval** of *newly installed* noise barriers (to compare results with specific quantified requirements).

[1] the quick method is now called the « SOPRA » method

[2] the full methods are those described within EN-1793-5 [3] and -6 [4] , based on the QUIESST research [2]

[3] for inspection tests, one must be very careful: those tests being done by visual inspection, they cannot give relevant results about the *airborne sound insulation* if defects are hidden (e.g.: degraded interior acoustic materials)

2.1 Monitoring of already installed noise barriers

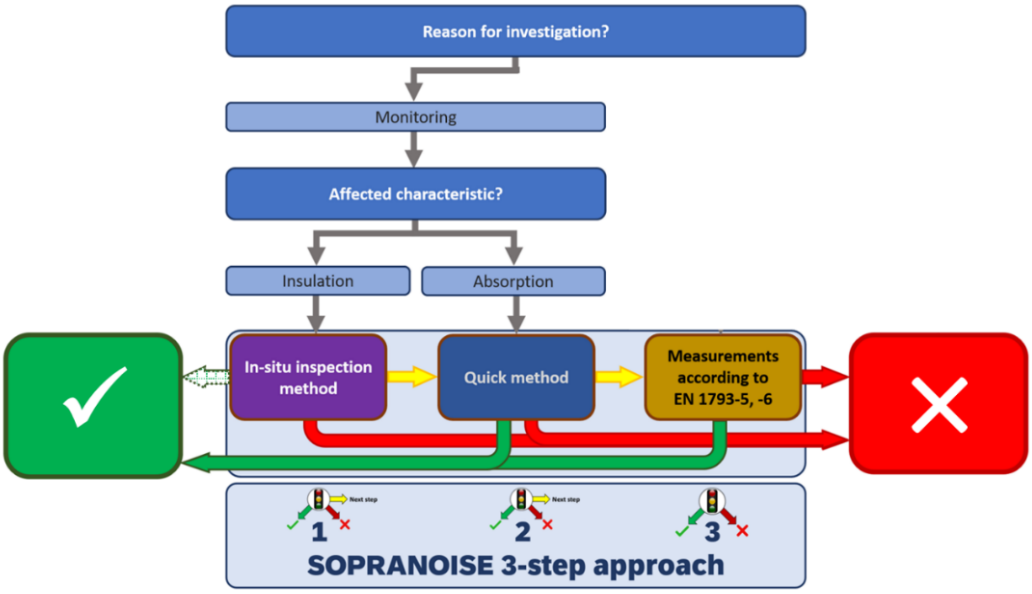


Figure 5: SOPRANOISE 3 successive steps when monitoring the performance of installed NB.

If the reason for investigation is to monitor the noise barrier, Figure 5 shows how to use the SOPRANOISE 3-Step approach. The process is the following:

Airborne sound insulation

"In-situ inspections" are useful to check if installed noise barriers have defects that can affect its global IL performance (not exactly *intrinsic* but *extrinsic*): they could be used to monitor *up to what extent* a NB can be considered as efficient to reduce noise in the environment it has to protect. However, "In-situ inspections" cannot give any quantified value of the *intrinsic airborne sound insulation*. The SOPRANOISE 3-Step approach applies as follow:

- **Step 1**: "In-situ inspections"; then, if results of the inspections are clear and fair, then "acceptance" or "rejection" can be decided[4]; otherwise further investigations have to be done;
- **Step 2**: (tests with) the Quick / SOPRA method; then, if the results of the test carried out are clear and fair, "acceptance" or "rejection" can be decided; otherwise further investigations have to be done;
- **Step 3**: (test with) standard '"full" methods.

Sound absorption/reflection

Based on visual inspections, the "In-situ inspections" can only characterize the *airborne sound insulation*: in that way, for *sound absorption/reflection*, one has to go directly to Step 2: Quick / SOPRA method and/or to Step 3: standard '"full" methods.

Whatever for *airborne sound insulation* or for *sound absorption/reflection* authorities should fix their own *rejection criteria* for Step 2; however, an *official approval* of the NB performances can only be done by Step 3. In other words, the acceptance criterion for a newly built NB should refer to measurement results according to the full EN standards, namely EN 1793-5 and EN 1793-6 (Step 3) and cannot be done only based on Step 1 or Step 2.

[4] for inspection tests, one must be very careful : those tests being done by visual inspection, they cannot give relevant results about the *airborne sound insulation* if defects are hidden (e.g. : degraded interior acoustic materials)

2.2 Approval of y installed noise barriers

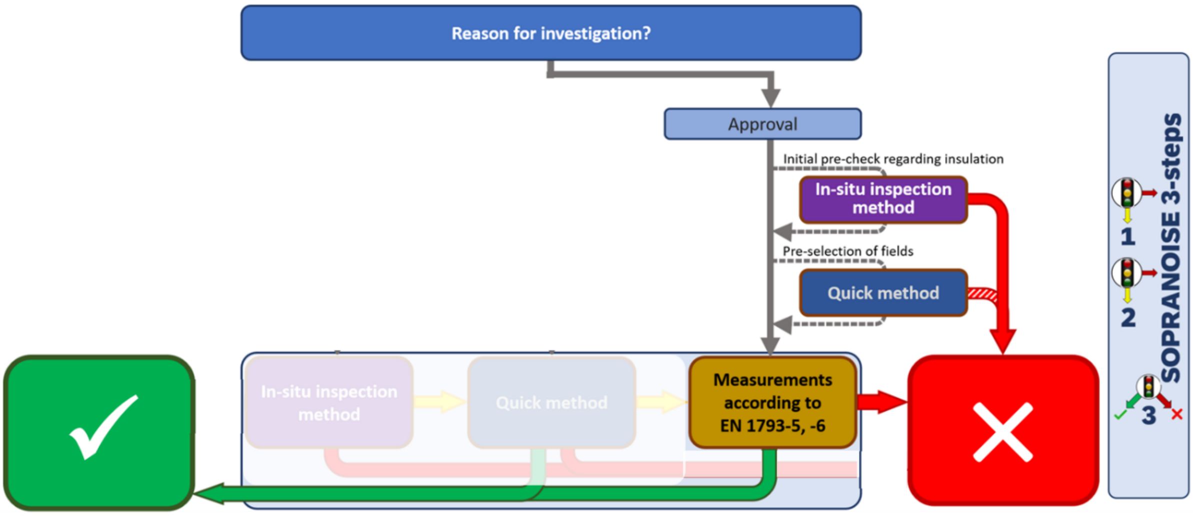


Figure 6: SOPRANOISE 3 successive steps to official approval of installed NB.

If the reason for investigation is the approval of noise barriers, Figure 6 shows how to use the SOPRANOISE 3-Step approach. The process is the following:

If authorities are willing to officially approve the intrinsic acoustic performance of installed NB, the only methods certifying that the measured values are those ones described in the standard '"full" methods EN 1793-5 (for *sound absorption / reflection*) and EN 1793-6 (for *airborne sound insulation*). In the SOPRANOISE 3-Step approach, this is the **Step 3**.

However,

- **Step 1**: "In-situ inspections" *could be very useful* before any other ones.

  Those inspections could usefully detect if defects are already existing that could degrade the IL performance: in such cases, the defective items have to be directly rejected before carrying out any further tests[6].

- **Step 2**: the Quick / SOPRA method *could be very useful* before applying the standard '"full" methods: as this method is much quicker, safer and less expensive that the standard '"full" methods, it is the best method for having a relevant overview on the whole length of NB, with possibility to establish relevant statistics and justify relevant sampling of *where to limit* the tests to be carried out with the standard '"full" methods.

  Additionally, authorities could also fix criteria of rejection at this level[7].

The next chapters will shortly introduce the Step 1 and Step 2 methods: for more details, the reader could refer to the SOPRANOISE deliverables D3.1 *Final report on the main results of WP3 (including M3.1, M3.2 and M3.3) – In-situ inspection tools* [5] and D4.2 *Report on the validation of the new quick methods in-situ with recommendations for proper use* [6] , while for Step 3, the references are directly the corresponding EN 1793-5 [3] and EN 1793-6 [4] (CEN) standards.

[6] warning: no acceptance can be given at this stage.
[7] warning: no acceptance can be given at this stage.

3 Step 1: In-situ inspections

Carefully done, *inspections* are the simplest and cost effective tools to monitor any equipment all along its lifetime, this can be usefully applied to Noise Barriers: monitoring NB is the best way to maintain those to stay functional, safe and effective over years.

The *in-situ inspections* procedure developed in WP3 corresponds to the first step of the SOPRANOISE 3-steps approach.

This *in-situ inspection* procedure targets *simplified acoustic assessments*[8] of possible degradations of *airborne sound insulation*. It is mainly based on *visual* inspections and *characterization of defects* in NB, focusing on their possible effect on *sound transmission* and on the *insertion loss*. It is based on inputs which can be made by visually inspecting a noise barrier and protocol, among other describing information, the size and position of identified defects.

If degradations of the *sound absorption* performance are suspected, inspections are not sufficient to conclude on their effect on the *global acoustic performance* of the NB: assessing *sound absorption* the requires to pass to Step 2 and Step 3[9]. However, during inspections, some evident degradations could directly be reported as: destroyed hard porous materials or evident degradation of mineral wool inside cassettes. In such cases, inspections could be used to directly conclude that the absorptive materials have to be replaced, but their real effect on the IL has not been studied in this research.

The reader can usefully refer to the SOPRANOISE deliverables D3.1 *Final report on the main results of WP3 (including M3.1, M3.2 and M3.3) – In-situ inspection tools* [5] for more details about how inspection tools have been designed and just ified, while the following presentation aims to quickly show with an example how simple and useful those *inspection tools* are.

3.1 Short description of the in-situ inspection procedure

The acoustic inspection protocol is set up as an Excel file consisting of five different sheets, as shown in Figure 7: the *inspector* can use this Excel document to obtain a first assessment of the acoustic condition of the noise barrier. This can be partly prepared in advance and finalised in an interactive manner during the general inspection routines on a portable device.

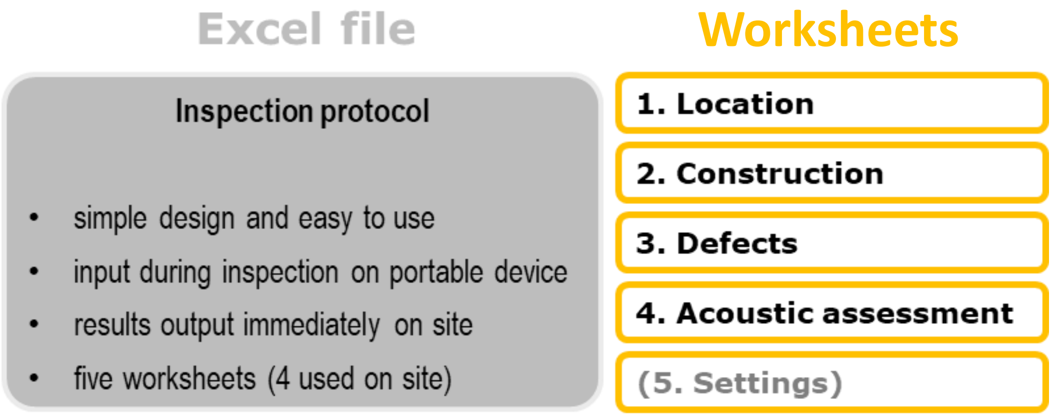


Figure 7: principles of the in-situ inspection protocol for assessing airborne sound insulation performance of already installed NB.

[8] important reminder: *inspection tools* are not intended to be used for *approvals* of newly built noise barriers, that can only be done by *quantitative* measurements. The intended purpose of the inspections is to *qualitatively assess installed noise barriers and prioritize their maintenance*.

[9] of course, *qualitative* assessment of the *sound absorptive materials*, if visible, could always *be done* by inspections (mostly to monitor *degradations*), but *fair conclusions* on the *global acoustic performance* cannot be given from those.

As shown in Figure 7, main features are:

- the procedure can easily be implemented in a general inspection routine of any existing road / railway inspection routines;
- few inputs are required and, thanks to dropdown lists and check boxes, the data entry process is quick and easy;
- the global settings are adjustable via a worksheet that can be protected;
- the results of the acoustic *qualitative assessment* are directly available in a self-explanatory “traffic-light” rating and a critical radius (see 3.2.3) .

The purpose and content of the five worksheets is the following :

1. **Location (inputs):**

   General information about the location of the noise barrier is entered on this sheet, mainly as free text.

2. **Construction (inputs):**

   The maximum of information on the materials used in the design of the noise barrier has to be entered in order to document the actual condition of the NB (while the calculation itself is independent from the inputs made in this sheet, records on the noise barrier construction are always useful for further investigations).

3. **Defects (inputs):**

   This sheet is the main input sheet of the inspection protocol: all information on the detected defects are filled in there. Except for the field number and additional notes, all inputs can be selected from a dropdown list or via check boxes. This makes the actual inspection process fast and easy to handle on site. Entry fields in the ‘Defects’ sheet are:

   - field number,
   - noise barrier side,
   - field height,
   - defect location,
   - type/cause of defect (view through, position (vertical and horizontal), size (vertical and horizontal),
   - additional notes.

4. **Acoustic assessment (outputs):**

   This sheet presents the results of the acoustic *inspection* and is a *pure output sheet*, where each considered noise barrier field is listed with the assessed acoustic condition and a critical radius of influence. Two different types of acoustic assessment are included: the result of the calculation *for each noise barrier field individually*: from this, the severity (in the acoustic sense) of a single leak becomes evident. However, in general more than one leak can occur in the same noise barrier field or in neighbouring noise barrier fields. Thus, for a comprehensive *overall acoustic assessment* of the whole NB, the superposition of leaks close to each other is also considered. The calculated “Critical radius” is the radius of influence behind the noise barrier up to which the leak has a non-negligible effect on the acoustic performance of the noise barrier.

5. **(Settings):**

   It is possible to tune few global parameters. In general, those modifications are not necessary since the default values serve as a good approximation within the accuracy of the method. However, to prevent incorrect use of this sheet, it can be also locked.

3.2 *Example: inspection of an acrylic glass NB in Germany*

Figure 8: View of the noise barrier used for this demo example

3.2.1 Preparation before inspection

Before starting the actual inspection, the first two sheets of the inspection protocol (‘1. Location‘ and ’2.Construction‘) should be filled in with the location data and the information on the material composition of the noise barrier: this should be preferably done before going on site, in order to ease the process on site.

Sheet 1: Location (inputs to be preferably filled before inspection)

SOPRANOISE in-situ inspection protocol for noise barriers

Sheet 1 - Location

road name	1	B42	
near	2	Oberwalluf	
emergency lane	3	no	
from/to km	4 (a,b)	45,7	52,9
direction	5	Frankfurt	
from/to coordinates	6 (a-d)	50,044433	8,137693
		50,044482	8,137751

Figure 9: Screenshot of *Sheet 1: Location* with demo entries

The corresponding successive entries of the example are (Figure 9):

1. The first entry is the abbreviation and corresponding number of the motorway/road. In the example, it is the federal highway with the designation "**B42**".

2. The second entry describes which city or municipality is nearby. At the given location of the example, the noise barrier is located near “**Oberwalluf**”.

3. The third field asks whether the road has an emergency lane between the first traffic lane and the noise barrier at the inspected location. In the example there is none, consequently “**no**” is chosen.

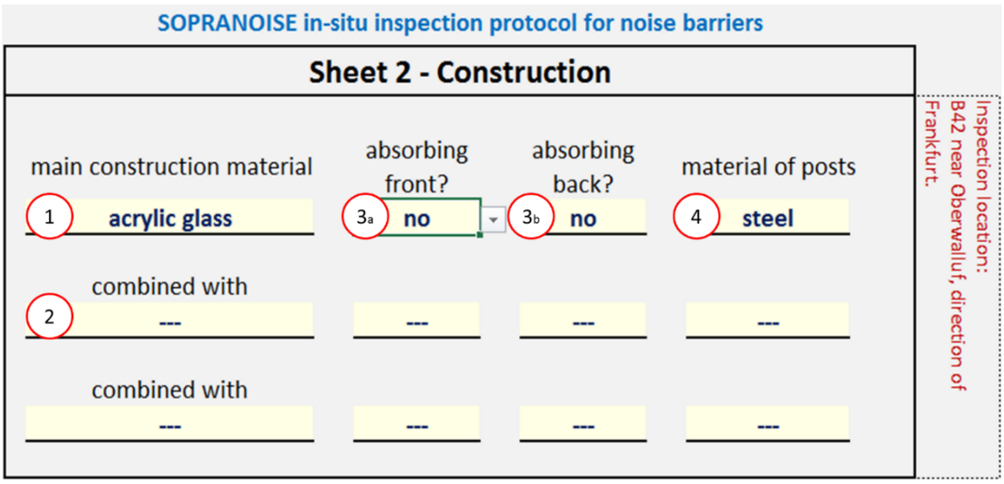
4. In fields 4a and 4b, the beginning and end of the inspected section is entered on the basis of the kilometres of the motorway. In the example, the noise barrier was inspected from the kilometre marker “**45.7**” to “**52.9**”. This means that 7.2 km were inspected.

5. Field five represents the direction of travel to define the side of the road on which the inspected noise barrier is located. For the example of the federal highway B42 used here, this leads in the direction of “**Frankfurt**”.

6. The last four fields indicate the GPS coordinates of the beginning (from) and end (to) of the inspected section as taken from any navigational system. In the example, the GPS coordinates of the inspected noise barrier section are “**50.044433 | 8.137693**” and “**50.044482 | 8.137751**”.

4 and 6 are in principle interchangeable and describe the same facts. However, the fields 4a and 4b give greater attention to the inspected length of the noise barrier, whereas the coordinates in the fields 6a - d give more attention to the position of the inspected noise barrier section on the map. Thus, of course, both entries can be made, but one of the two is also sufficient.

Sheet 2: Construction (inputs to be preferably filled before inspection)


SOPRANOISE in-situ inspection protocol for noise barriers

Sheet 2 - Construction

main construction material	absorbing front?	absorbing back?	material of posts
1 acrylic glass	3a no	3b no	4 steel
combined with 2 ---	---	---	---
combined with ---	---	---	---

Figure 10: Screenshot of *Sheet 2: Construction* with demo entries

The input options are here divided into three lines, each line representing one material used in the noise barrier construction. If the barrier consists of only one material along its entire inspected length, filling in one line will be sufficient.

A total of three materials can be entered, one main material and two materials with which the main material was combined. Further input fields deal with the absorptive properties of the noise barrier and the material of the posts.

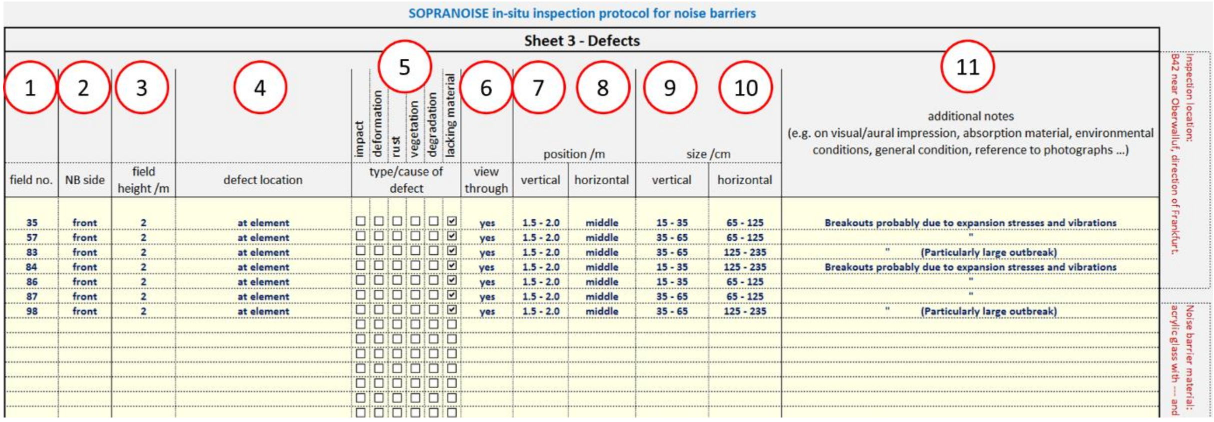
The corresponding successive entries of this example are (Figure 10).

1. In a dropdown menu the user can choose between the most commonly used materials for noise barriers: steel, aluminium, wood, concrete, wood-concrete, stone, gabion, earth, plastics, acrylic glass, polycarbonate and mineral glass.
   In the example, the main construction material of the noise barrier is "**acrylic glass**".
2. If required, for the second and third material the same choices can be made.
   In the example, the concrete elements are not combined with elements made of another material.
3. The front and back side of the acrylic glass elements are fully reflective. Therefore, the selection is "**no** | **no**".
4. For the material of the posts, one can choose between steel and concrete.
   In the example, the posts are made of "**steel**".

Additionally, there is a summary box at the right side of the input block with the most important information of the sheet 'Location'. This side header serves for a better assignment of the sheets in printouts.

3.2.2 In-situ inspections

Sheet 3: Defects (inputs corresponding to the in-situ inspections)



SOPRANOISE in-situ inspection protocol for noise barriers

Sheet 3 - Defects

1 field no.	2 NB side	3 field height /m	4 defect location	5 type/cause of defect: impact	deformation	rust	vegetation	degradation	lacking material	6 view through	7 position /m: vertical	8 position /m: horizontal	9 size /cm: vertical	10 size /cm: horizontal	11 additional notes (e.g. on visual/aural impression, absorption material, environmental conditions, general condition, reference to photographs ...)
35	front	2	at element	☐	☐	☐	☐	☐	☑	yes	1.5 - 2.0	middle	15 - 35	65 - 125	Breakouts probably due to expansion stresses and vibrations
57	front	2	at element	☐	☐	☐	☐	☐	☑	yes	1.5 - 2.0	middle	35 - 65	65 - 125	"
83	front	2	at element	☐	☐	☐	☐	☐	☑	yes	1.5 - 2.0	middle	35 - 65	125 - 235	" (Particularly large outbreak)
84	front	2	at element	☐	☐	☐	☐	☐	☑	yes	1.5 - 2.0	middle	15 - 35	125 - 235	Breakouts probably due to expansion stresses and vibrations
86	front	2	at element	☐	☐	☐	☐	☐	☑	yes	1.5 - 2.0	middle	15 - 35	65 - 125	"
87	front	2	at element	☐	☐	☐	☐	☐	☑	yes	1.5 - 2.0	middle	35 - 65	65 - 125	"
98	front	2	at element	☐	☐	☐	☐	☐	☑	yes	1.5 - 2.0	middle	35 - 65	125 - 235	" (Particularly large outbreak)
				☐	☐	☐	☐	☐	☐						
				☐	☐	☐	☐	☐	☐						
				☐	☐	☐	☐	☐	☐						
				☐	☐	☐	☐	☐	☐						
				☐	☐	☐	☐	☐	☐						
				☐	☐	☐	☐	☐	☐						
				☐	☐	☐	☐	☐	☐						

Figure 11: Screenshot of *Sheet 3: Defects* with demo entries

This is the main sheet of the in-situ inspection protocol and the only one to has to be filled in on site during the inspection. The information protocolled here is mostly relevant for the *acoustic assessment* calculated on the next sheet. Each row of the table represents a defect that has been identified. All information describing the position, size and type of damage must be entered. The check boxes can be used to indicate how the damage looks like and presumably occurred.

The corresponding successive entries of the example are (Figure 11):

1. **field no:** number of the noise barrier field. Whole-number values can be entered freely in numerical form. The numbers can be simply determined by numbering every field from the beginning to the end of the inspected noise barrier section. *The entry is important for the 'Acoustic assessment' sheet.* The first defect in the example is located at field no. "**35**" of the inspected noise barrier.
2. **NB side:** noise barrier side under inspection. Possible entries are "front" or "back". "front" is the side facing the road, "back" is the side facing the residents. The inspected side of the example is the "**front**" side.

3 **field height /m:** height of the entire noise barrier field. Possible entries are numerical values in 0.5 m steps. *The entry is important for the 'Acoustic assessment' sheet.* In the present example, the height of the noise barrier field is "**2**" m.

4 **defect location:** location of the defect at the noise barrier field. For the entry you can choose between "at element", "at post", "between elements", "between element and post" or "between element and foundation". Following the example, the defect is located "**at element**".

5 **type/cause of defect:** this column is divided into six fields with check boxes; every check box stands for a single type or cause of a defect. The six indicators are "impact", "deformation", "rust", "vegetation", "degradation" and "lacking material", multiple selections are possible. In the example, parts of some glass elements are broken off at the top edge, so "**lacking material**" is chosen.

6 **view through:** how deep is the damage? Is it only on the surface or does it go all the way through the wall? Possible entries are "yes" or "no". *The entry is important for the 'Acoustic assessment' sheet.* In the described example it is possible to look through the noise barrier, thus "**yes**" is chosen here.

7 **position /m vertical:** position of the centre of the defect in vertical direction in ranges of 0.5 m. Choose from a list beginning from "0.0 – 0.5" m up to "9.5 – 10.0" m. *The entry is important for the 'Acoustic assessment' sheet.* If uncertain between two ranges, choose the lowest one. In the example, the defect is vertically located in the height range "**1.5 - 2.0**" m.

8 **position horizontal:** locates the position in the noise barrier field. The purpose of this entry is to facilitate retrieval in case of re-inspection. The entry has no influence on the acoustic assessment. Possible entries are "left", "middle" or "right". The defect in the example is horizontally located in the "**middle**" of the inspected noise barrier field.

9 **size /cm vertical:** describes the medium vertical extension of the defect under investigation. Choose from a list ranging from small defects smaller than 4 cm ("< 4") to a defect extension larger than 415 cm ("> 415"), with sizes gradually doubling in extension. *The entry is important for the 'Acoustic assessment' sheet.* If uncertain between two ranges, choose the lowest one. In the example the average size of the defect in vertical direction is in the range between 15 and 35 cm, thus "**15 - 35**" is selected.

10 **size /cm horizontal:** describes the medium horizontal extension of the defect under investigation. Choose from a list ranging from small defects smaller than 4 cm ("< 4") to a defect extension larger than 415 cm ("> 415"), with sizes gradually doubling in extension. *The entry is important for the 'Acoustic assessment' sheet.* If uncertain between two ranges, choose the lowest one. The average size of the defect in the example in horizontal direction is in between 65 and 125 cm, thus "**65** - **125**" is selected.

11 **additional notes:** in this last column additional notes can be entered to describe the defect in free text or record other information that may be important for evaluating and/or repairing the damage. Together with photos taken, better decisions can be made in the office. In the example, the inspector entered the notes "**Breakouts probably due to expansion stresses and vibrations**".

Additionally, there is a summary box at the right side of the input block with the most important information of the sheets 'Location' and 'Construction'. This side header serves for a better assignment of the sheets in printouts.

3.2.3 Results

Sheet 4: Acoustic assessment (results / outcomes of the in-situ inspections)

SOPRANOISE in-situ inspection protocol for noise barriers

Sheet 4 - Acoustic assessment

Assessment for each NB field individually

field no.	acoustic condition	critical radius /m
35	G	5
57	G	9
83	Q	17
84	G	8
86	G	3
87	G	9
98	Q	17

Estimated overall assessment (superposition)

field no.	acoustic condition	critical radius /m
35	G	5
57	G	9
83	Q	33
84	Q	34
86	Q	32
87	Q	29
98	Q	17
		0
		0
		0
		0

Inspection location:
B42 near Oberwalluf, direction of Frankfurt.

Figure 12: Screenshot of *sheet 4: Acoustic assessment* with demo output results

After completing the entries in *input sheets* 1 to 3, *Sheet 4: Acoustic assessment* becomes available. This sheet is an *output sheet*: no entries are possible here.

The corresponding results of the in-situ inspections done on our example are presented in Figure 12: this sheet immediately shows an estimation of the degradation of the acoustic performance caused by the corresponding recorded damages.

Two types of assessment are available:

- The left table shows the effect of each defect considered individually.
- The right table shows the estimated total effect of all recorded defects in superposition: this naturally results in more extensive areas of influence, which can be directly read off in the numerical value of the "critical radius".

Both sides of this representation have a meaning: while on the right side the estimated *overall* assessment of the acoustic condition can be read, on the left side it can be quickly recognised which damage has a large or small impact on this overall result.

In those tables, the acoustic consequences of the damages are shown by different ways:

- *acoustic condition:*
  a traffic light colour rating using a **red**, yellow and **green** colour scheme: **green** stands for a *tolerable* influence of the damage and **red** for such a large damage that a repair is unavoidable to restore the necessary acoustic properties. In the yellow transition area, further acoustic checks should then be carried out using Step 2.
- *critical radius:*
  the estimated radius of influence of the damage of influence.

3.2.4 Additional settings

Sheet 5: Settings (available on special request, otherwise locked)

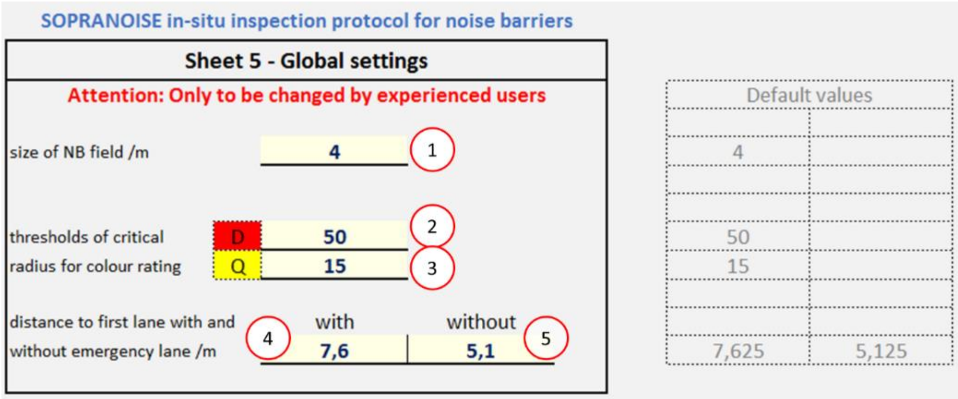


Figure 13: Screenshot of fifth sheet 'Settings' with default values

Demo values are shown in Figure 13, its right table states the pre-set default values.

Usually, no changes are necessary here.

Changes can have a great effect on the acoustic assessment and should be restricted to specialists usage: therefore, the sheet is locked against accidental entries.

4 Step 2: Quick method (SOPRA method)

4.1 Introduction

The quick method developed in WP4 - also called SOPRA method - corresponds to the second step of the SOPRANOISE 3-steps approach.

The quick method is a quick test 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. The application procedure is summarized in a compact way in report D4.2 *Report on the validation of the new quick methods in-situ with recommendations for proper use* [6] , referring to EN 1793-5 [3] and EN 1793-6 [4] 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. 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, 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 wherever they are, what could also be alongside roads or railways, and using a sound field similar to those coming from those surface traffic, i.e. a direct sound field. Thus, the above tasks could in principle be performed using the EN standards. However, their application requires 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. 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 Step 1 (in-situ inspections) and Step 2 (quick method) are very useful tools to prepare the selection of the elements / posts to be tested in full.

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 14).

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 15).

The ratio of the power spectra of the direct and the reflected components gives the basis for calculating the “quick” sound reflection index.

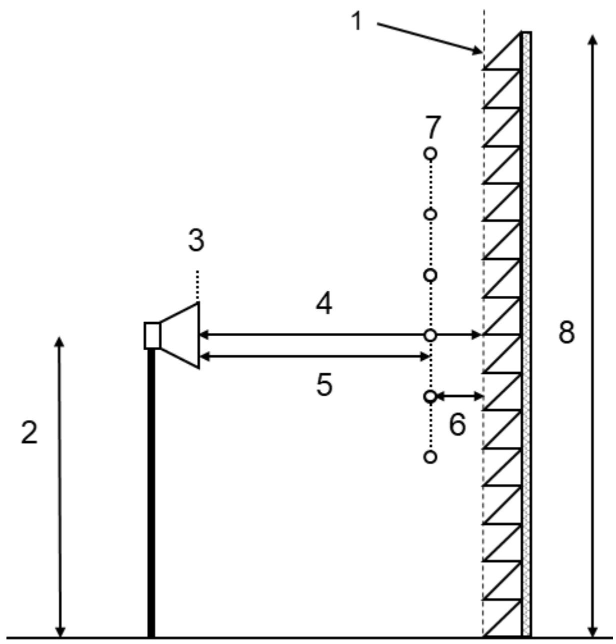


Figure 14. (not to scale) Sketch of the sound source and the microphone antenna in front of the road traffic noise reducing device under test for sound reflection index measurements.

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]

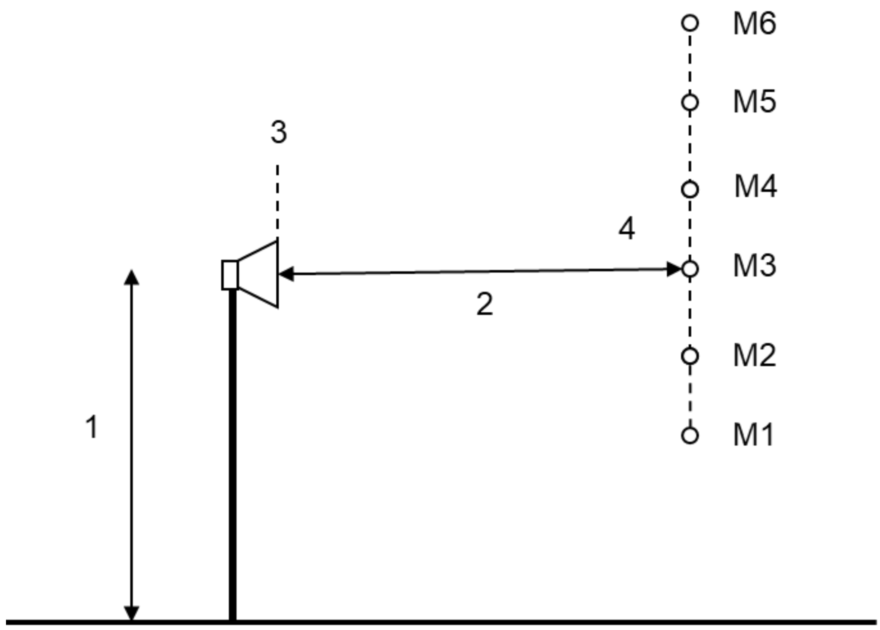


Figure 15. (not to scale) Sketch of the set-up for the reference “free-field” sound measurement for the determination of the sound reflection index. The microphones are labelled “M1” to “M6” from the bottom to the top.

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

The measured quantity is the “quick” reflection index RI_Q as a function of frequency, in one-third octave bands from 200 Hz to 5 kHz. Limitations to the frequency range apply for noise barriers with a height less than 4 m.

The equipment consists of a lightweight sound source and a linear microphone antenna, see Figure 16. 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.

The sound source is placed facing the noise barrier side exposed to road traffic noise, at a height *of* 2,00 m and placed so that the horizontal distance of the loudspeaker front panel to the reference surface of the noise barrier is 1,50 m.

The microphone antenna is placed in 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 a height of 2 m; iii) the shortest distance of the microphone n. 3 (M3) to the reference surface is 0,25 m.

All necessary processing is done in situ using a small control and processing device, purposely designed for SOPRANOISE.

The signal processing is very similar to that in EN 1793-5 (input signal, time analysis window, etc.) and a single-number rating, called $DL_{RI,Q}$ can be calculated from the one-third frequency band values.

For further details see report D4.2 *Report on the validation of the new quick methods in-situ with recommendations for proper use* [6] and EN 1793-5 [3] .

Figure 16. 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.

4.2.2 Example: sound reflection tests on a metal noise barrier

This sub-chapter gives an example of results on a metal noise barrier (borrowed from report D4.2 *Report on the validation of the new quick methods in-situ with recommendations for proper use*): the noise barrier under test is made up of modular aluminium 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 17).

Figure 17. Microphone antenna, loudspeaker and control device in place for the 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.

Figure 18 presents the results of all 20 quick measurements, averaged over the four microphones M2 to M5. The bottom microphone, M1 has been excluded to avoid the reflection of the sound waves emitted by the loudspeaker over the reflecting ground inside the analysis window. The top microphone, M6, has been excluded to avoid the strong influence of the sound waves emitted by the loudspeaker and diffracted back by the top edge of the noise barrier. The black lines are the results of a full EN 1793-5 test done 3 months before (continuous line) and the tolerance interval defined by adding or subtracting to/from the EN 1793-5 measured value the measurement uncertainty at 95% confidence level (dotted lines). The general trend of the full EN measurement is captured quite well from the 400 Hz one-third octave band.

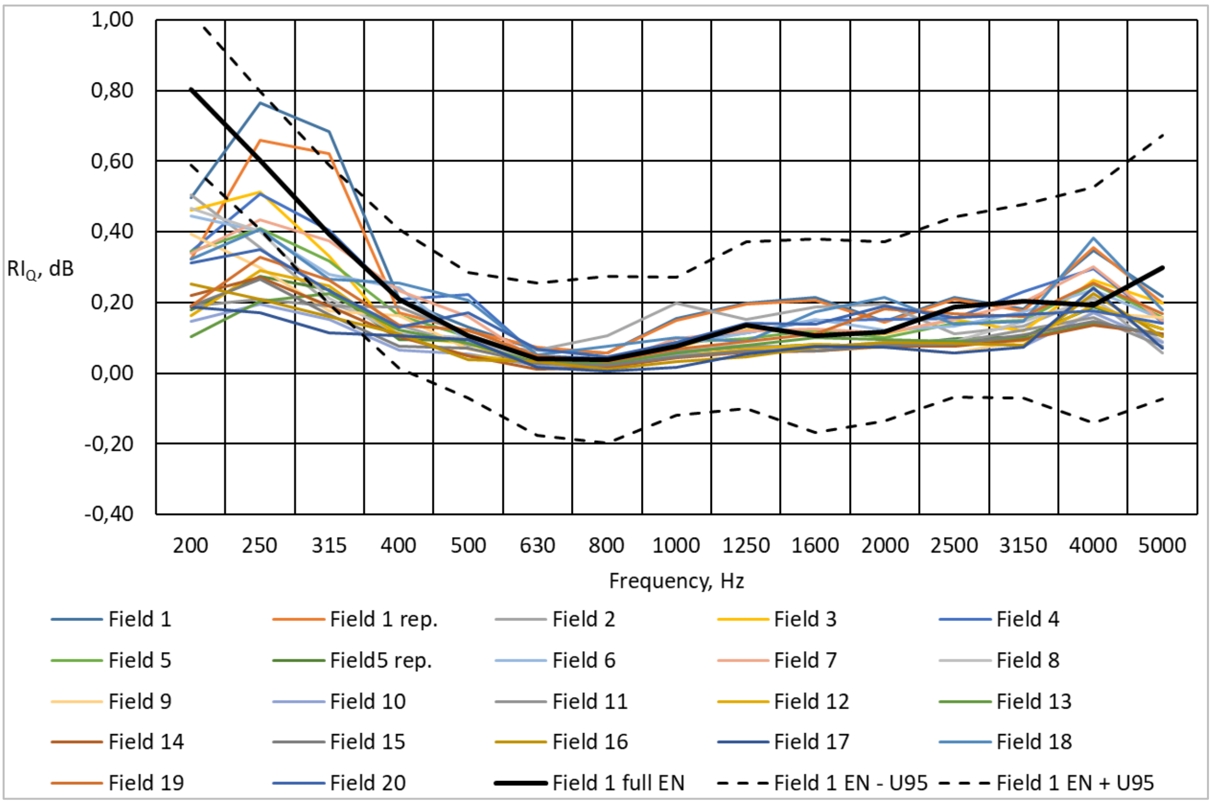


Figure 18. Colour lines: RI_Q spectra obtained with the quick method on the metal noise barrier for 20 different fields (2 repeated). Average over mic. M2-M5. Black continuous line: result of a previous EN 1793-5 measurement on a single field. Black dashed lines: EN 1793-5 measured value ± the expanded measurement uncertainty at 95% confidence level.

Figure 19 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 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 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 again Figure 17.

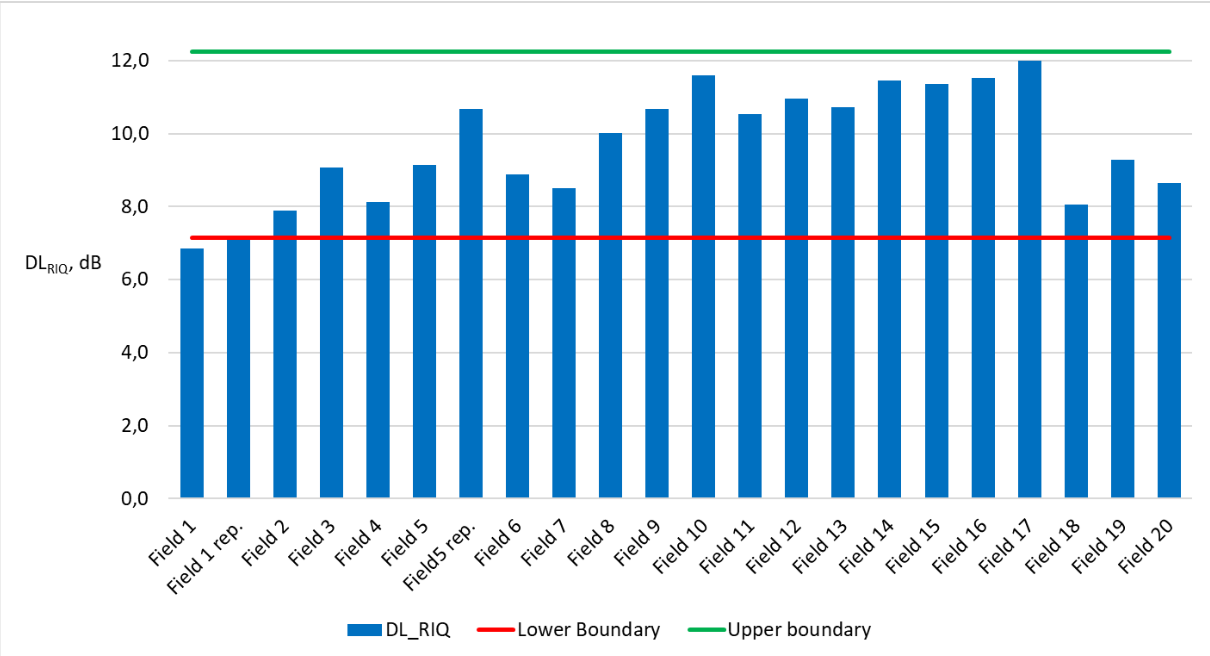


Figure 19. Differences of the single-number ratings of the individual RI_Q measurements on 20 different fields (plus 2 repetitions) from their average value. The lower and upper boundary lines are calculated as ±1,645 times the standard deviation.

4.3 *Airborne 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 20).

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 21).

The power spectra of the direct wave and the transmitted wave give the basis for calculating the “quick” sound insulation index.

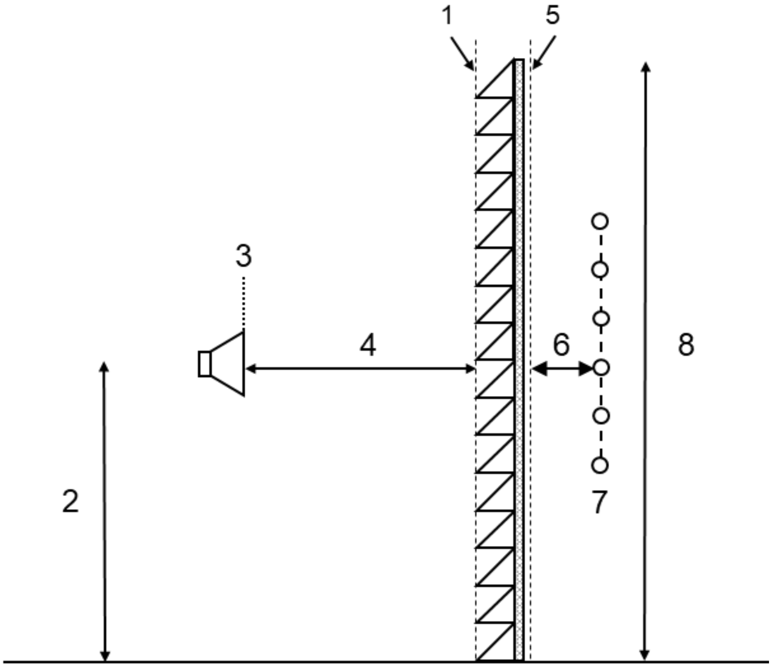


Figure 20. (not to scale) Sketch of the sound source and the microphone antenna close to the noise barrier under test for quick sound insulation index measurements.

Key

1 Loudspeaker reference surface

2 Source reference height, h_S [m]

3 Loudspeaker front panel

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

5 Microphone reference surface

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

7 Microphone antenna

8 Noise barrier height, h_B [m]

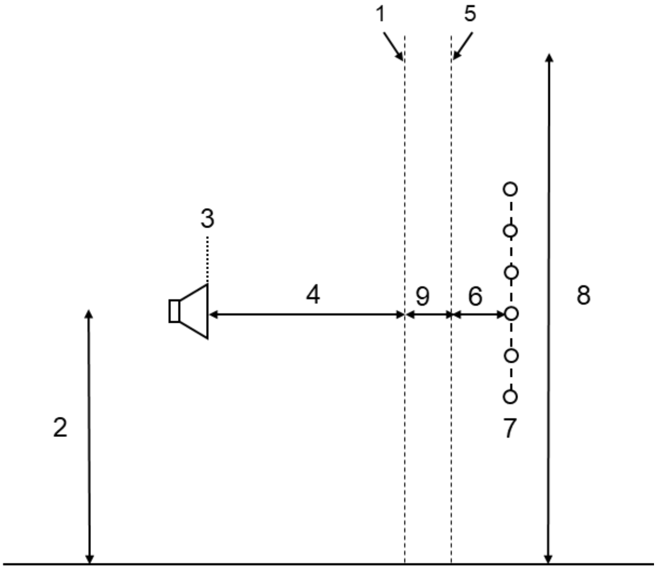


Figure 21. (not to scale) Sketch of the of the set-up for the reference “free-field” sound measurement for the determination of the quick sound insulation index.

Key

1 Loudspeaker reference surface

2 Source reference height, h_S [m]

3 Loudspeaker front panel

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

5 Microphone reference surface

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

7 Microphone antenna

8 Noise barrier height, h_B [m]

9 Nominal noise barrier thickness, t_B [m]

The measured quantity is the “quick” sound insulation index SI_Q as a function of frequency, in one-third octave bands from 200 Hz to 5 kHz. Limitations to the frequency range apply for noise barriers with a height less than 4 m.

The equipment consists of the same lightweight sound source and a linear microphone antenna used for measuring sound reflection, see Figure 16. 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.

The sound source is placed facing the noise barrier side exposed to road traffic noise, at a height of 2,00 m and placed so that the horizontal distance of the loudspeaker front panel to the reference surface of the noise barrier is 1,00 m.

The microphone antenna is placed in 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 a height *of* 2 m; iii) the shortest distance of the microphone n. 3 (M3) to the microphone reference surface is 0,25 m.

All necessary processing is done in situ using the same small control and processing device used for sound reflection measurements.

The signal processing is very similar to that in EN 1793-6 (input signal, time analysis window, etc.) and a single-number rating, called $DL_{SI,Q}$ can be calculated from the one-third frequency band values.

For further details see report D4.2 *Report on the validation of the new quick methods in-situ with recommendations for proper use* [6] and EN 1793-6 [4] .

4.3.2 Example: sound insulation tests on a metal noise barrier

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 22 and Figure 23.

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

Figure 23. Loudspeaker in place for the quick sound insulation index measurements.

Figure 24 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.

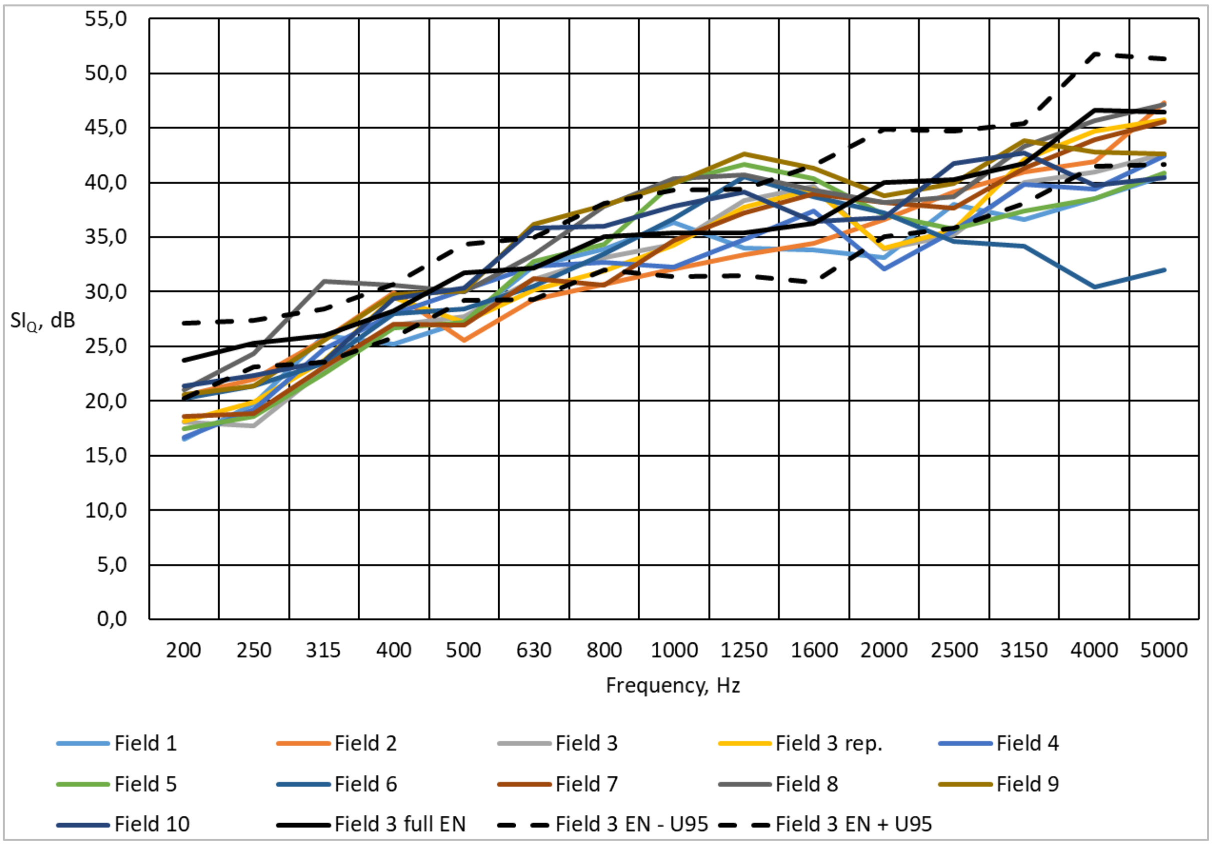


Figure 24. Colour lines: SI_Q spectra obtained with the quick method on the metal noise barrier for 10 different fields (1 tested twice). Average over microphones M2-M5. Black continuous line: result of a previous EN 1793-6 measurement on field n. 1. Black dashed lines: EN 1793-6 measured value plus or minus the expanded measurement uncertainty at 95% confidence level.

Figure 25 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).

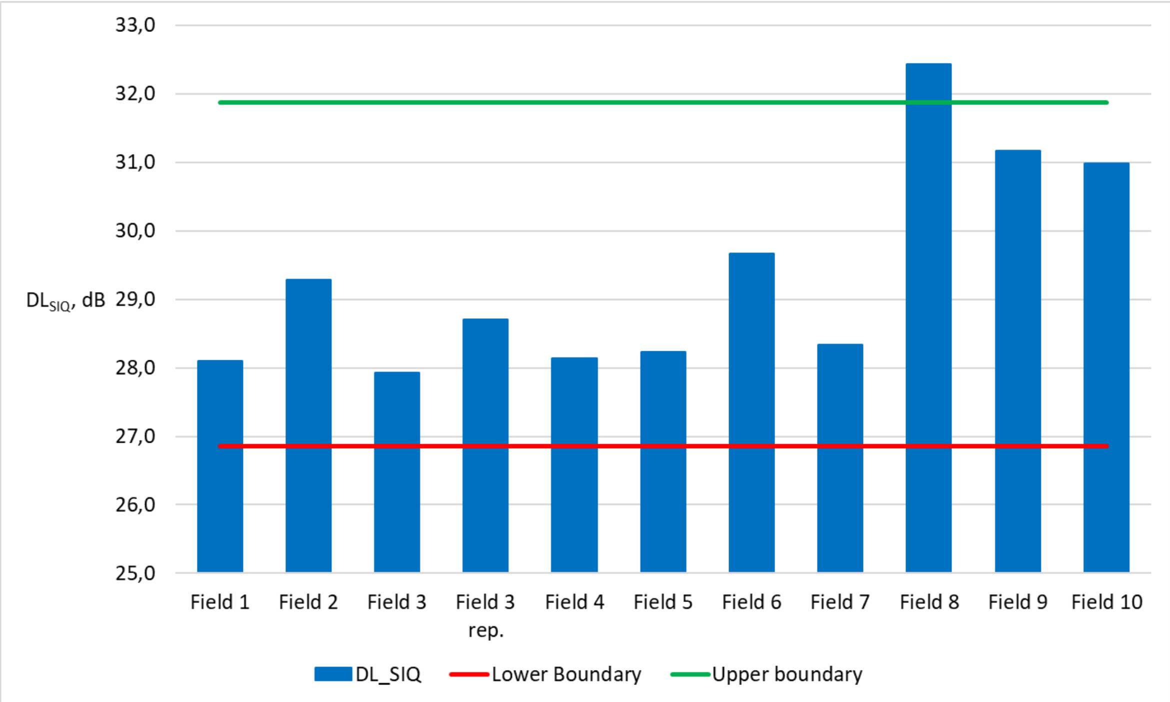


Figure 25. Differences of the single-number ratings of the individual SI_Q measurements on 10 different fields (+ 1 repetition) from their average value. The lower and upper boundary lines are calculated as ±1,645 times the standard deviation.

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 again Figure 23.

5 Step 3: In-situ "full tests"

Step 3 should normally come after Step 1 and / or Step 2, as those methods can help to reduce the efforts requested by the "full tests":

- not only by simply rejecting NB elements that are obviously damaged in such extent that no accurate method is really necessary to conclude (Step 1)
- but also by establishing a relevant sample of long NB that could be representative of the whole NB length: in such a way, the amount of "full tests" could be limited to a lower amount of relevant elements (Step 2).

"Full tests" methods are fully described in (CEN) standards EN 1793-5 [3] for *sound absorption* and EN 1793-6 [4] for *airborne sound insulation*: those methods are well known by the NB market stakeholders and do not require more information within the present SOPRANOISE task.

6 Conclusions

Characterizing the intrinsic *acoustic performances* (*sound absorption / reflection*, *airborne sound insulation*) of Noise Barriers is important to be assured that those NB will correctly (continue to) reduce noise in the environment they have to protect.

As today's NB could often be very long and can be made of a huge amount of elements, testing exhaustively all of those elements with "full tests" as EN 1793-5 [3] and for *airborne sound insulation* EN 1793-6 [4] is not realistic, nor affordable.

The SOPRANOISE 3-step approach allows to place the right effort and money to the right level of analysis: from the easiest (but less accurate) way, up to the most accurate one.

SOPRANOISE has now described and justified the 2 new methods:

- **Step 1**: *In-situ Inspections* method[11], and
- **Step 2**: *SOPRA* method

Thanks to their lower cost and safer use, much more systematic monitoring possibilities are now available thanks to Step 1 and Step 2, while Step 2 is a very good method to "overview" NB and to justify relevant sampling of NB elements.

The next task will now be to submit those 2 new methods to standardization.

[11] last reminder : In-situ inspections are not designed for characterizing sound absorption

7 References

[1] CEDR Technical Report 2017-02, State of the art in managing road traffic noise: noise barriers, Brussels, Belgium (2017).

[2] J-P. Clairbois, F. de Roo, M. Garai, M. Conter, J. Defrance, C. Oltean-Dumbrava, C. Durso. Guidebook to noise reducing devices optimisation. European Project QUIESST (FP7-SST-2008-RTD-1 SCP8-GA-2009-233730), Brussels, Belgium (2012).

[3] EN 1793-5:2016+AC:2018, *Road traffic noise reducing devices - Test method for determining the acoustic performance - Part 5: Intrinsic characteristics - In situ values of sound reflection under direct sound field conditions,* 2018.

[4] EN 1793-6:2018, *Road traffic noise reducing devices - Test method for determining the acoustic performance - Part 6: In situ values of airborne sound insulation under direct sound field conditions,* 2018.

[5] M. Chudalla, F. Strigari, W. Bartolomaeus, *SOPRANOISE Deliverable D3.1, Final report on the main results of WP3 (including M3.1, M3.2 and M3.3) – In-situ inspection tools-*, 2021.

[6] M. Garai, P. Guidorzi, *SOPRANOISE Deliverable D4.2, Report on the validation of the new quick methods in-situ with recommendations for proper use*, 2022.

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CEDR TRANSNATIONAL ROAD RESEARCH PROGRAMME 2018

SOPRANOISE

M5.5 Final Scientific Report and Guidelines

April 7, 2022

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Foreword

Integrating two different topics, this report is logically presented in two parts:

- Part A is dedicated to the SOPRANOISE Final Scientific Report, while
- Part B is dedicated to the Guidelines written based on the outcomes of the SOPRANOISE research.

Part A: Final Scientific Report

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1 Introduction

The **SOPRANOISE** acronym means: *"**S**ecuring and **O**ptimizing the **P**erformance of **R**oad tr**A**ffic Noise Barriers with **N**ew meth**O**ds and **I**n-**S**itu **E**valuation".*

This research addresses new tools to assess the acoustic performances of noise barriers as they are effectively used along road and railway networks.

The target is to facilitate the assessment of the acoustic performances of noise barriers, not only at or just after their installation, but also throughout their whole lifetime: at the end of this research, one can say that the target has been successfully reached.

A new concept of assessment has been developed: **the SOPRANOISE 3-step approach** (see Figure 1). It allows to place the right effort and money to the right level of assessment: from the easiest (but less accurate) way, up to the most accurate one (i.e.: the standardised methods EN 1793-5 [3] [4] and EN 1793-6 [4]), following an "engineering progressive approach".

To reach the objective, the missing two first levels have been now filled by the purposely designed *In-situ inspection* and the *"SOPRA" quick method*.

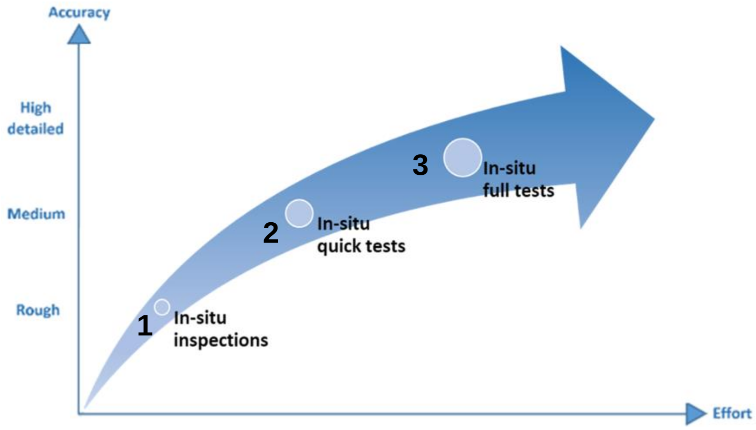

Figure 1: SOPRANOISE 3-steps approach to characterize the *intrinsic* acoustic characteristics of installed noise barriers: from less accurate but easy methods up to the more accurate full in-situ tests.

At the end of each step, relevant decisions can be taken whether fair conclusions could be drawn, otherwise further tests are still necessary (see main principles of the three successive steps in Figure 2).

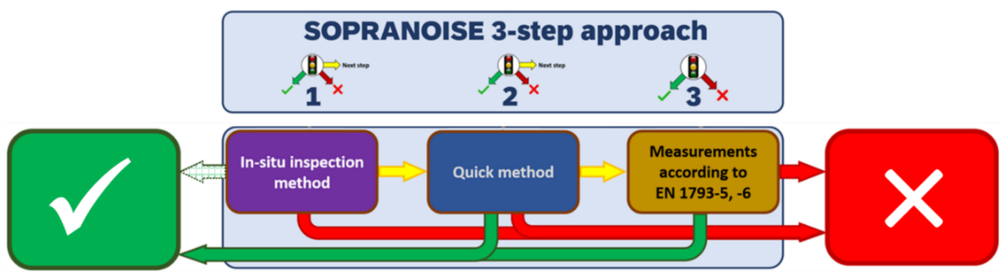

Figure 2: Main principles of the SOPRANOISE successive 3 step approach to characterize the *intrinsic* acoustic characteristics of installed noise barriers

This document is the final scientific report of the research: it recalls its objectives and the way the research has been done, then it logically refers to all the successive scientific reports delivered from the beginning up to the end of the research, and finally it states its conclusions and major outcomes that could now improve the assessment of noise barriers.

1.1 Background, issues and objectives

Noise barriers are extensively used by NRAs as effective devices to reduce road noise; railways companies are doing the same for their networks. In order to optimize and secure the performance of noise barriers, one has to understand that their *overall* acoustic performance to reduce road noise towards the environment is a complex process that includes not only the noise barriers implementation and the geometrical dimensions, but also their “intrinsic quality” (i.e.: the acoustic quality directly pertaining to the products themselves). NRAs logically draft relevant specifications that contractors and manufacturers of noise barriers products have to respect, in order to: not only to correspond to the design hypotheses, but also to guarantee the overall acoustic performances all along their lifetime cycle.

In order to verify if installed noise barriers are effectively respecting the tender requirements, one has to test those in a fair way: *as they are installed* (involving the quality of the products and how they are installed), which means under real conditions alongside roads (and railways), and following their *intended use* (i.e.: under *direct sound field* conditions).

Since 1990, CEN/TC226/WG6[1] drafted standards on the acoustic and non-acoustic *intrinsic* performances of Noise Reducing Devices, a broader family of road equipment products that also includes noise barriers. CEN/TC226/WG6/TG1 is specially dedicated to the acoustic characteristics and drafted a relevant framework of supporting standards: EN1793-1[1] (sound absorption under *diffuse sound field* conditions - can only be done in laboratory), -2 [2] (airborne sound insulation under *diffuse sound field* conditions - can only be done in laboratory), -5 [3] (sound reflection under *direct sound field* conditions) and -6 [4] (airborne sound insulation under *direct sound field* conditions). Those last two standardised methods are the only relevant to the *intended use* of “free standing noise barriers”; they also have the advantage to allow measurements almost everywhere, what is here very relevant while approving and / or monitoring installed noise barriers.

This is already and increasingly done by NRAs to characterize installed noise barriers[2]. However, EN1793-5 [3] and -6 [4] methods require quite lengthy tests that could also be affected by practical conditions (weather conditions, safety, accessibility…), as well as the need of expert users: this can limit their use alongside roads.

While always keeping the possibility to use EN1793-5 [3] and -6 [4] on site, there is a need for new methods that could be easier, faster and safer.

Some NRAs already undertake *in-situ* inspections in order to monitor the integrity of the different parts of their road/railway equipment. Those inspections are the easiest and cheapest tools to investigate installed noise barriers: implementing such *in-situ* inspections in a more systematic way, integrating the acoustic characteristics is a real plus that can save time and money.

For quantitative assessments (by measurements), new “quick methods” had to be designed in order to be applicable in a much more systematic and affordable way than the one allowed by the “full” EN1793-5 [3] and -6 [4] : this has been done successfully and led to the brand new and validated quick “SOPRA” method.

As noise barrier performances can decrease over time, while infrastructure administrators need to control and maintain the noise reduction at all stages of their lifetime, there was a clear need to better understand how noise barriers could reduce noise and keep their original acoustic performances along their whole lifetime.

SOPRANOISE successfully replies to all those needs.

[1] CEN/TC226/WG6: Comité Européen de Normalisation / Technical committee 226: road equipment / Working Group 6: Noise Reducing Devices

[2] In recent years, many NRAs apply EN1793-5 and -6 as noise barriers acceptance and check after installation, as well as to investigate the evolution of the acoustic performances all along their lifecycle.

1.2 Structure of the research

Figure 3 presents the SOPRANOISE structure.

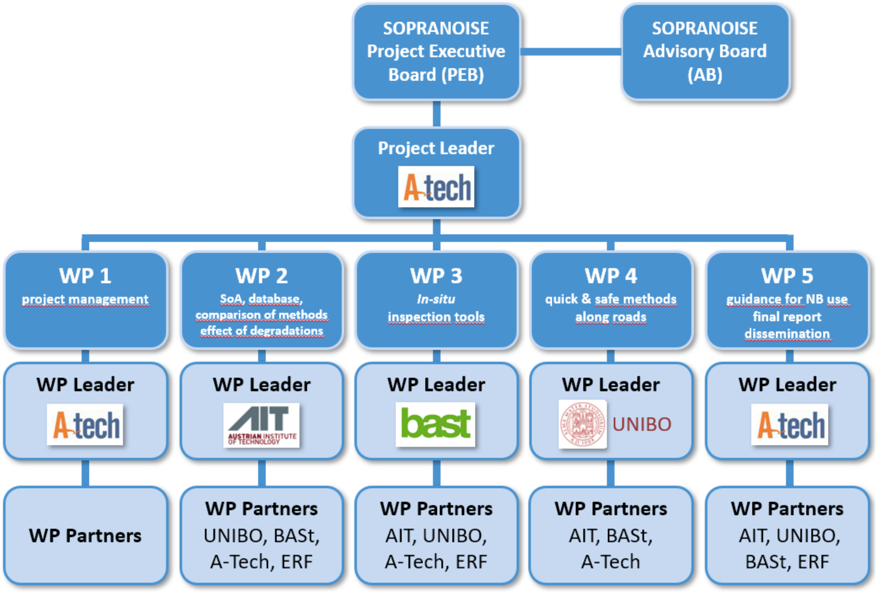

Figure 3: SOPRANOISE whole project structure.

The SOPRANOISE consortium included the following main partners: A-Tech, AIT, UNIBO, BASt and ERF. Each work package had a WP leader and also involved all the other partners. CEDR closely followed and helped the research as representing the relevant road authorities, while ERF (European Road Federations) represents the noise barriers market stakeholders (manufacturers and installers).

WP1 concerned the "project management", while the scientific parts have been managed within the Work Packages WP2 to WP5:

- WP 2 had three objectives: (1) State of the Art about physical significance, correlations and possible trends (if any) between the diffuse sound field methods (EN1793-1 [1] and -2 [2]) and the corresponding direct sound field methods (EN1793-5 [3] and -6 [4]); (2) update and extension of the database of the acoustic performances of EU noise barriers products, and (3) up to what extent degradations could affect / reduce the global noise barrier performance (insertion loss). This last objective was the basement of the new in-situ method of WP3.
- WP3 was dedicated to in-situ inspections methods: such methods will now allow to assess the noise barriers acoustic performances in a much more cost effective and systematic way.
- WP4 was fully dedicated to design the new "SOPRA" quick and safe methods to measure in-situ sound absorption and airborne sound insulation: from an in-depth analysis of the existing techniques, up to the design and validation of the method and equipment.
- Finally, WP5 has achieved: a website on which the public deliverables are available, a report on the physical behaviour of noise barriers, a State of the Art on today's noise barriers use in the EU, and the synthesis of the research within this final scientific report, as well as its main outcomes stated in comprehensive guidelines on how to improve the use of noise barriers.

The scientific outcomes of each Work Package are presented in their corresponding reports: this document directly refers the reader to those.

2 WP 2: SOA, database, effect of degradations

The general objective of WP 2 of the SOPRANOISE project was to provide both theoretical and practical background information on measurement methods of the acoustic performance of noise barriers and on meaningful results. This work package achieved the following tasks:

- Task 2.1: Review of the physical significance of EN1793-1, -2, -5 and -6 (AIT, UNIBO):

  In this task a systematic research on the State of the Art regarding correlations available in literature and possible trends between measurement results between methods under diffuse sound field conditions and methods under direct sound field conditions was performed. The results of this task are summarised in Deliverable D2.1 [5] which also represents the achievements of milestone M2.1 as a final output of task T2.1. This task report has been also included as a first part of Deliverable D2.2 [6] .

- Task 2.2: Update and analysis of noise barrier database including new current measurements (AIT):

  This task had to update and analyse the noise barrier database including new current measurements. It focused on the extension of the relevant database of EU noise barriers that was started within the QUIESST project, including single-number ratings and third-octave band spectra from manufactured products, and already installed noise barriers. The SOPRANOISE database now shows facts and figures about acoustic performances obtained from both the diffuse sound field and direct sound field methods, together with a better understanding of the respective significance, similarities, and differences of these standardized methods, improving data analysis and correlations between these methods. The outcomes of this task are summarised in the report T2.2, showing the achievement of milestone M2.2, which was integrated in Deliverable D2.2 [6] .

- Task 2.3: Influence of acoustic degradation of noise barriers on the total noise reduction (BASt, AIT, UNIBO, A-Tech):

  Within this task, the effect of acoustic degradation on the global acoustic performance of noise barriers was considered in detail. The results yield the theoretical background for the assessment of the acoustic degradation due to leaks in a noise barrier and allow to calculate the (acoustic) radius of influence for different leak characteristics. This work builds the basis for the in-situ inspection procedure developed in WP3 and is reported in the task T2.3 report, which shows the achievement of milestone M2.3 and represents the third and last part of the Deliverable D2.2 [6] .

As a main output of WP2 the **SOPRANOISE database** now contains results on 448 different noise barriers manufactured and installed by 58 different noise barrier manufacturers or construction companies, from 9 different European countries (Austria, Belgium, France, Germany, Ireland, Italy, Spain, The Netherlands, and United Kingdom) for a total of **2029 datasets and 1263 single number ratings**. The measurements collected have been performed by 39 different testing laboratories from the European countries listed before.

Regarding the correlations between the single-number rating of *sound absorption* under diffuse sound field conditions $DL_{\alpha,\mathrm{NRD}}$ and the single-number rating of sound reflection under direct sound field conditions DL_{RI}, the statistical distribution shows clearly that **values obtained with the method according to EN 1793-1 are in general considerably higher than the values obtained with the methods according to EN 1793-5**.

Therefore, the **median value for the method according to EN 1793-1 is between 9 and 10 dB, while for the method according to EN 1793-5 the median value is around 6 dB.** In conclusion, in regard to the correlation between results of *sound absorption* under diffuse sound field condition and *sound reflection* under direct sound field condition, only very rough estimates are possible, which are limited to low sound absorbing samples with no practical use for certification or quality assurance purposes.

Regarding the correlations between the single-number rating of *airborne sound insulation* under diffuse sound field conditions DL_{R} and the single-number rating of *airborne sound insulation* under direct sound field conditions DL_{SI} the statistical distributions shows that **values obtained according to EN 1793-2 are in general slightly lower than the values obtained according to EN 1793-6**. Element values are in general higher than results at the post, while the global values are between these values. The **median value for the method according to EN 1793-2 is around 28 dB, while for the method according to EN 1793-6 the median values are around 34 dB for element, 30 dB for post and 31 dB for global values**. Furthermore, the shape of the probability functions is rather similar, nevertheless the values according to EN 1793-6 can reach higher values up to 66 dB (especially at the acoustic element), while the values according to EN 1793-1 reach maximum values around 50 dB. In conclusion, in regard to the correlation between results of *airborne sound insulation* under diffuse sound field conditions and results under direct sound field conditions, a promising fit could be achieved due to the wide data range. Nevertheless, the significant uncertainties of the regression models must be considered when predictions are made, which also limits the practicality of using prediction models for certification or quality assurance purposes.

Finally, the possibilities of finding correlations between the measurement methods were pushed to its limits regarding the use of external information and applying statistical linear and non-linear multi-variate regression models as an empirical approach. Possible further research on these topics has been delineated in the last chapter of Deliverable D2.2 [6] .

3 WP 3: *in-situ* inspection tools

In WP3, an inspection protocol that can also be implemented in existing inspection routines was developed for recording and evaluating acoustically relevant damage to noise barriers: it consists of an *Excel* tool with accompanying explanatory descriptions for its application. With this tool, it is possible to log damage and prioritise pending repairs to ensure noise protection.

The following WP3 tasks have been achieved:

- Task 3.1: Review of existing *in-situ* inspection tools (BASt, AIT, A-Tech, UNIBO):

  Based on a questionnaire sent to the CEDR Member States (covering European Road Authorities and Research Institutes), information was collected on existing inspection routines and knowledge / experience on various aspects of noise barrier acoustic performance. The outcomes of this task are summarised in the report on T3.1, which is integrated in Deliverable D3.1 [7] .

- Task 3.2: Development and testing of methods based on *in-situ* inspection (BASt, AIT, UNIBO)

  In task, the acoustic *in-situ* inspection procedure was developed. It allows an initial acoustic assessment of the effect of defects on the insertion loss of noise barriers. The inspection is mainly based on a visual screening, from which the detected defects are characterised. Based on a theoretical model and considering the recorded defect characteristics and geometrical parameters, an acoustic radius of influence is calculated, leading to the acoustic rating of the inspection. Tests showed that this calculation method provides a realistic assessment of the acoustic effects of leakages in a noise barrier. All outcomes of T3.2 are summarised in the report T3.2, which is integrated in Deliverable D3.1 [7] .

- Task 3.3: Description of the *in-situ* inspection tools and reporting (BASt, AIT, UNIBO)

  In the third task of this WP3, the *in-situ* inspection procedure was further developed based on several feedbacks and additional testing. The scope of application was defined and the corresponding user-oriented documents containing all information required for the implementation and understanding of the inspection procedure were prepared. In particular, herein it is emphasized that (i) the *in-situ* inspection yields a first evaluation for the acoustic degradation due to one or more defects in a noise barrier; (ii) the underlying theoretical model is a qualitative approximation with several simplified assumptions; (iii) no conclusions regarding sound absorption properties can be drawn and (iv) for the legal approval of a noise barrier quantitative acoustic measurements will always be necessary.

  With the availability of

  - the ***Excel* file** to record defects recognised at inspections,
  - the **short description** of the in-situ inspection procedure and
  - the **manual** of the in-situ inspection protocol

  every road administration is now given the opportunity to carry out a first qualitative acoustic assessment of noise barriers using visual inspection. The outcomes of this final task of WP3 are summarised in the T3.3 report, which is integrated in Deliverable D3.1 [7] .

With the completion of WP3, the first stage of the progressive SOPRANOISE 3-step approach is fully developed. The result is a hands-on in-situ inspection procedure for the qualitative evaluation of the degradation effect in the acoustic insertion loss of a noise barrier due to leaks.

The inspection protocol allows a simple and fast application on site, can be used in parallel to existing inspection procedures, follows a physics-based approach and has a well-defined scope and user-oriented documentation.

Regarding the future application of the in-situ inspection tool, the implementation of the inspection protocol can be easily modified to adapt new requirements. In this context, especially the practical experiences from users and other demands raised by stakeholders will surely help to further improve the procedure and eventually realise a relevant tool for facilitating the systematic characterisation of noise barriers.

4 WP 4: quick and safe methods alongside roads

WP4 had to develop the quick methods corresponding to the second step of the 3-step SOPRANOISE approach. The quick methods are **measurement** methods for determining the noise barrier *intrinsic* characteristics *sound absorption* and *airborne sound insulation* under a direct sound field, i.e., in non-reverberant conditions.

The following WP4 tasks have been achieved:

- Task 4.1: Review of existing quick methods (UNIBO, AIT, A-Tech):

  The existing proposals of quick methods for determining the *intrinsic* acoustical characteristics of noise barriers have been analysed and compared with a multi-criteria approach. The outcomes of T4.1 are summarised in the internal Report T4.1.

- Task 4.2: Development and testing of reliable quick methods (UNIBO AIT, BASt)

  Relying on the outcomes of Task T4.1 and the researchers' experience in developing the EN full 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 quick methods give reliable and quantitative conclusions on the noise barrier performances. The same laboratory samples have been tested with the quick methods and with the full EN methods to assess the degree of correlation of the quick methods with the acknowledged qualification standards. At the end of Task T4.2, the new quick method was ready for validation in real on-site conditions. The outcomes of T4.2 are presented in the Deliverable D4.1[8] .

- Task 4.3: Validation of quick methods by comparison with full methods *in-situ* (UNIBO, AIT, A-Tech, BASt)

  This task has been accomplished by UNIBO applying both the new quick methods and the EN 1793-5 and EN 1793-6 methods on noise barriers installed along the A22 motorway connecting Northern-Italy to Austria. Metal barriers and timber barriers have been tested. It has been proved that the quick methods allow to test many more noise barrier fields in the same time, at the price of a slightly reduced accuracy, compared to the full EN standards. AIT performed laboratory measurements with their own (also purposely newly developed equipment) in order to systematically compare the new developed quick methods with the full EN standards and evaluate the repeatability of the quick method, which proved to be excellent. Task T4.3 successfully ended with Milestone M4.3 .

- Task 4.4: Report on the new quick methods (UNIBO, AIT, A-Tech, BASt)

  Task T4.4 was devoted to write the final WP4 report on the new quick methods developed in the frame of SOPRANOISE (Deliverable D4.2 [9]). 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 Task 4.4 report also includes some recommendations for proper use of the quick methods:

i) an acceptance criterion for each individual quick measurement, based on a statistical approach;

ii) two proposals, following two different approaches, for a “sampling criterion” when applying the quick methods to a noise barrier, in order to assess the representativity of the acquired sample of quick measurements. Clearly this is something that goes beyond the SOPRANOISE project; investigations on this topic will continue after the end of the project.

The outcomes of T4.4 is the Deliverable D4.2 [9] .

The new quick methods 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 methods is easy and quick.

Thus, **the quick methods 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. 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 of SOPRANOISE approach) could be selected.

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. With the fading out of the pandemic, it is hoped that this research could be done in-situ along some main motorways. At the same time, the acquisition of many more data, which is possible with the new quick methods, should allow to assess the in-situ repeatability of the quick methods and its correlation with the full EN method.

5 WP 5: final report and guidelines for noise barriers use

On one hand, WP5 assembles the results of the research in a comprehensive manner and, on the other hand, delivers guidelines to provide an improved and wider practical approach on how to consider noise barriers as powerful tools to reduce road noise: all of this from planning, design, procurement, control, use and maintenance phases within a long-term perspective.

The following WP5 tasks have been achieved:

- Task 5.1: Website implementation (ERF, A-Tech): https://www.enbf.org/sopranoise/

- Task 5.2: Physical behaviour of noise barriers / acoustic intrinsic performances (A-Tech, UNIBO)

  This task had to clarify how noise barriers could be efficient (or not) and up to what extent their *intrinsic* performances do act in the overall process of sound propagation toward the environment. Starting from the basics (i.e.: the physical phenomena), up to the final *noise reduction* in the environment (the Insertion Loss IL), throughout all the factors involved in the process (both the *extrinsic* and *intrinsic* ones), its report is presented as the T5.2 report, integrated within the Deliverable D5.1 [10] .

- Task 5.3: State of art on the today's noise barriers use within the EU Market (A-Tech, AIT, BASt, UNIBO, ERF)

  The aim of this task was to understand how different authorities, NRAs, railway companies are considering, specifying and using noise barriers along their respective networks. A questionnaire with seven key questions has been circulated to numerous EU Noise Barriers stakeholders: a database of the 32 replies has been built and analysed: this survey is presented under theT5.3 report, integrated within the Deliverable D5.1 [10] .

- Task 5.4: How to assess the noise barriers acoustic performances (A-Tech, AIT, BASt, UNIBO)

  This task assembles the outcomes of the In-situ Inspections methods (WP3) and the ones of the new "SOPRA" method (WP4), summarizing the SOPRANOISE 3- step approach to characterise the intrinsic acoustic performances of noise barriers: it is presented as the T5.4 report, integrated within the Deliverable D5.2 [11] .

- Task 5.5: Drafting the Guidelines and the final scientific report (A-Tech, AIT, BASt, UNIBO, ERF)

  This task is divided in two parts: *Part A* is the present scientific report that summarizes the outcomes of the scientific work packages WP2 to 5, while *Part B* are the guidelines, aiming to provide guidance to NRAs and railway companies to better use of noise barriers thanks to all the outcomes of this research; M5.5 is actually the present report and it is integrated into Deliverable D5.2 [11] that also includes the report on task T5.4.

- Task 5.6: Final event (ERF, A-Tech)

  The final event is integrated in the CEDR 2018 Noise and Nuisance - Final Conference held on 7-8 June 2022 in Liège, Belgium.

At the end of this research an important task will be started:

- Task 5.7: transmission to CEN standardization (A-Tech, UNIBO)

  The *in-situ* inspection methods and tools as well as the new SOPRA method will be transmitted to CEN TC226/WG6 (for roads, Ir. Jean-Pierre Clairbois being its convenor), and TC256/SC1/WG40 (for rail, Prof. Dr. Massimo Garai being its convenor) for standardization.

Apart the logic assembly of the different WP reports, the main WP5 outcomes are those of:

- Task 5.2 that summarises **how noise barriers could be efficient (or not) and up to what extent their *intrinsic* performances do act in the *overall noise reduction* of a noise barrier**;
- Task 5.3 that allows a **better understanding about how stakeholders are considering noise barriers**;
- and the **guidelines** (Part B of the present M5.5 report) that target a more holistic approach of the acoustic performances of noise barrier projects to be considered by the relevant authorities.

6 Conclusions

The objective of the SOPRANOISE research was to improve knowledge on how to assess the acoustic performance of noise barriers and to reach a new level of understanding on how noise barriers can be relevant tools to reduce road and railway noise.

To achieve this, the research has been subdivided into five Work Packages, four of those being the effective scientific research:

- Work Package 2, thanks to the assembly and the thorough analysis of **the purposely updated database** of the different test reports on the noise barriers intrinsic performances, **gives a relevant overview on how the noise barriers are characterized and what can be the realistic intrinsic performances we can expect from the EU noise barriers products**.
- Thanks to comprehensive research on how the extrinsic performance can be affected by degradations of noise barriers elements, **Work Package 3 designed and validated a new in-situ inspections method. This method allows easy and cheap investigations on the airborne sound insulation of installed noise barriers**.
- Work Package 4 successfully achieved the design of **the brand new "SOPRA" method: this method allows a quicker and safer procedure than the "full" standardized methods**. It works as a link in between those accurate but long and requiring standards and the simplest in-situ inspections. New equipment has been independently designed by the University of Bologna and the Austrian Institute of Technology and the "SOPRA" method has been validated.
- Finally, Work Package 5 assembled **relevant elements to understand how noise barriers can be better designed through a better understanding of how they work**, while a survey between EU noise barriers users shows **how different stakeholders do consider noise barriers on their networks**. **Guidelines based on the outcomes of SOPRANOISE** help NRA and railways authorities to **consider new noise barriers project with a holistic approach that can use all the benefits of the 3-step SOPRANOISE approach**.

As of today, SOPRANOISE significantly improves the knowledge and understanding of the acoustic performance of noise barriers, as well as how to assess their acoustic *intrinsic* performances, whenever and wherever they are installed.

The innovative SOPRANOISE 3-step approach ensures that the respective relevant method is used for the relevant analysis and allows NRA and railways infrastructures managers to better manage their noise barriers.

7 References

[1] EN 1793-1:2017, *Road traffic noise reducing devices - Test method for determining the acoustic performance - Part 1: Intrinsic characteristics of sound absorption under diffuse sound field conditions,* 2017.

[2] EN 1793-2:2018, *Road traffic noise reducing devices - Test method for determining the acoustic performance - Part 2: Intrinsic characteristics of airborne sound insulation under diffuse sound field conditions,* 2018.

[3] EN 1793-5:2016+AC:2018, *Road traffic noise reducing devices - Test method for determining the acoustic performance - Part 5: Intrinsic characteristics - In situ values of sound reflection under direct sound field conditions,* 2018.

[4] EN 1793-6:2018, *Road traffic noise reducing devices - Test method for determining the acoustic performance - Part 6: In situ values of airborne sound insulation under direct sound field conditions,* 2018.

[5] P. Reiter, A. Fuchs, et. al., *SOPRANOISE Deliverable D2.1, "Review of the physical significance of EN 1793-1, EN 1793-2, EN 1793-5 and EN 1793-6"*; 2020.

[6] M. Conter, et. al., *SOPRANOISE Deliverable D2.2, "Final report on the main results of WP2 (including M2.1, M2.2. and M2.3) – Acoustic assessment of the intrinsic performances of noise barriers"*; 2021.

[7] M. Chudalla, F. Strigari and W. Bartolomaeus, *SOPRANOISE Deliverable D3.1, "Final report on the main results of WP3 (including M3.1, M3.2 and M3.3) – In-situ inspection tools"*; 2021.

[8] M. Garai and P. Guidorzi, *SOPRANOISE Deliverable D4.1, "Report on the development of the new quick methods in laboratory"*; 2021

[9] M. Garai and P. Guidorzi, *SOPRANOISE Deliverable D4.2, "Report on the validation of the new quick methods in-situ with recommendations for proper use"*; 2022

[10] J-P. Clairbois, P. Houtave, N. Lebasi, C. Nicodème and M. Garai, *SOPRANOISE Deliverable D5.1,* "*WP5 Intermediate progress report including M5.1, M5.2 and M5.3"*; 2021

[11] J-P. Clairbois, M. Conter, M. Chudalla, F. Strigari, W. Bartolomaeus, M. Garai, N. Lebasi and C. Nicodème, *SOPRANOISE Deliverable D5.2, "SOPRANOISE Final report - Guidelines for NB use and scientific report"*, 2022

Part B:
Guidelines about the acoustic characteristics of noise barriers

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1 Introduction

The use of noise barriers dates to the early 1970s: many guidelines and standards have been already published about those. Nevertheless, there is still a strong demand from road and railway authorities, who are in charge to respect the environmental noise while managing traffic on their networks, to get effective guidance on a better, holistic and more sustainable approach of noise barriers projects.

Taking advantage of the outcomes of the SOPRANOISE research, those guidelines aim to provide practical guidance on noise barrier (NB) use in order to ensure *appropriate consideration* of their *acoustic* properties at all stages of their lifetime, i.e.:

1. **Before Noise Barrier Installation**:
   1.1. Noise Barrier Planning,
   1.2. Noise Barrier Design,
   1.3. Noise Barrier Procurement;
2. **At Noise Barrier Installation**: Approval (product and installation);
3. **During the Noise Barrier Effective Use / Lifetime**:
   2.1. Noise Barrier **Monitoring**,
   2.2. Noise Barrier **Lifetime Tests**,
   2.3. Noise Barrier **Maintenance**;
4. At Noise Barrier **End of Life**.

In any noise barrier project, in the first instance, we have to remember that we have to completely understand the *whole process*, ideally from “cradle to grave”, and be sure to also understand the “total cost of ownership” (TCO) corresponding to the total costs the authorities will have to support when “owning” this kind of road/railway equipment - without forgetting any stage of the equipment life cycle (LC).

Figure 4 shows the SOPRANOISE holistic approach (applied to the *acoustic* performances) that has been considered:

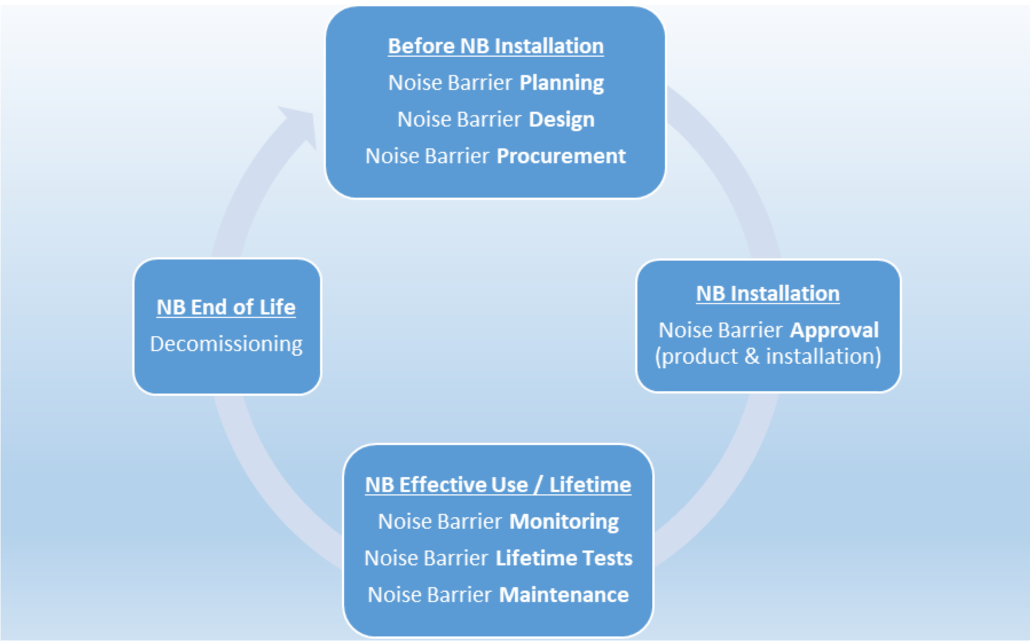


Figure 4: SOPRANOISE holistic approach of noise barriers projects

2 Before Noise Barrier Installation

When roads or railways impact their environment with excessive noise, noise barriers can provide very high and effective noise reduction but only if they are correctly designed and built.

In addition, as the road/railway equipment is installed for years, the design of noise barriers must ensure their ability to keep the noise reduction performance *all along their lifetime*.

At this stage of a new noise barrier project, one has the following successive steps:

Before NB Installation
Noise Barrier **Planning**
Noise Barrier **Design**
Noise Barrier **Procurement**

This Stage 1 is for sure the most important one, as it conditions how the noise barrier will be effective and sustainable throughout its whole lifetime.

2.1 Noise Barrier Planning

Why Road or Railway Authorities do procure and install noise barriers? In many cases, this is due to the development of new infrastructure and thus the Environmental Impact Assessment (EIA) process (including the noise impact assessment) that determined if barriers, or other acoustic mitigation, are required. In addition, the END and associated Noise Action Plans may also be a driver for the installation of barriers. Normally, it is up to the EIA or more specific surveys to conclude for installation of noise barriers: this chapter aims to recall how noise barriers can help "calming" the road traffic noise in its environment.

Noise barriers act during the noise propagation between (all) the (road or railway) vehicles[3] and the sensitive dwellings that are exposed to their noise. They can be considered appropriate for noise reductions from a few dB up to 10 - 12 dB in the case of normal "free-standing" noise barriers. Higher performances should consider heights "greater than usual" (e.g., 5 to 7 m or even more), or complex designs as canopies or partial road covers[4].

The SOPRANOISE Task 5.2 within Deliverable 5.1 [15] details all the main factors ruling the noise reduction of a noise barrier. The reader might refer to this report for a more detailed description.

A short overview of the *essentials* is presented hereafter.

From now on, we will speak about two kinds of characteristics:

- The ***extrinsic*** characteristics are all those characteristics not "directly attached" to the product(s) used in the projects, but very important in the final noise reduction (e.g.: height, length, relative location vehicles / barriers, but also a lot of other ones…).
- The ***intrinsic*** characteristics are those ones *inherent to the products* used to build up the barrier: they are also very important because they condition the noise reduction as far as *sound absorption/reflection*, *airborne sound transmission* and *sound diffraction* are concerned.

[3] From now on, 'traffic' will be used for both 'road' and 'railway' traffic.

[4] For performances over 20 dB, road covers and tunnels are more appropriate, but SOPRANOISE only considers "free-standing" noise barriers.

2.1.1 Noise *Reduction*: Insertion Loss IL

If we could sum up everything in one single sentence, it would be the following:

Whatever the situation, physics definitely rules the noise barrier effectiveness.

The noise *reduction* achieved by noise barriers in their environment is characterized by the **"Insertion Loss"** (**IL**: difference in *sound level* emitted by a vehicle/sound source **S** towards a receiver location **R** with and without the presence of the noise barrier with top **T**, which is located above the connecting line between **S** and **R,** see Figure 5).

IL is an *extrinsic* characteristic that involves a lot of factors, all influencing the final noise barrier effective performances:

- The *physical phenomena*:
  - ✓ *sound emission,*
  - ✓ *sound propagation,*
  - ✓ *sound absorption/reflection,*
  - ✓ *sound diffraction,* and
  - ✓ *airborne sound transmission;*

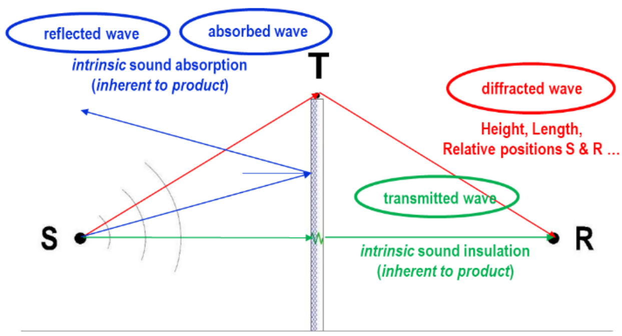


Figure 5 : Noise barriers, the physical phenomena

- The *emission* characteristics:
  - ✓ strongly depending on the type of vehicles (cars, trucks, trams, trains…);

- The *dimensions*:
  - ✓ height, length, volume (whatever the concerned objects),
  - ✓ source/receiver relative positions: topography and infrastructure profile,
  - ✓ frequency domain,
  - ✓ time scale;

- The *shape* of the objects:
  - ✓ vehicles (cars, trucks, trams, trains…),
  - ✓ barriers (flat vertical, flat inclined, non-flat, large noise barriers, with added devices…);

- The *sound propagation medium*:
  - ✓ air/weather conditions.

- The *intrinsic* characteristics (*inherent to the product* used):
  - ✓ *sound absorption/reflection*,
  - ✓ *airborne sound insulation*,
  - ✓ *intrinsic sound diffraction* at top edge.

All those factors are influencing the final IL performance.

2.1.2 The Physical Phenomena

2.1.2.1 Sound Reflection

Reflections on surfaces as noise barriers (but also any other surfaces) can have a negative effect: that is the reason why noise barriers are often made of sound absorbing materials, those materials being able to reduce the reflected sound energy.

Simple sound reflections

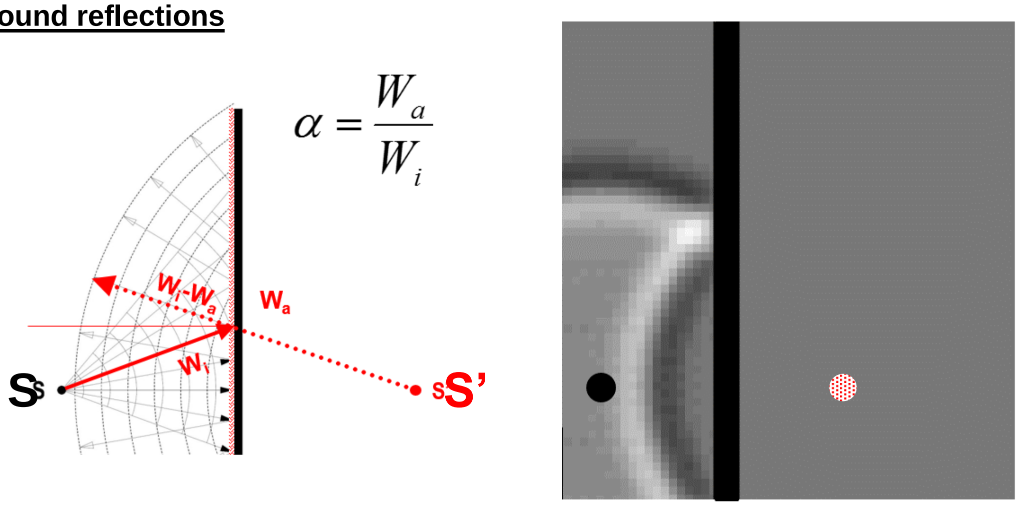
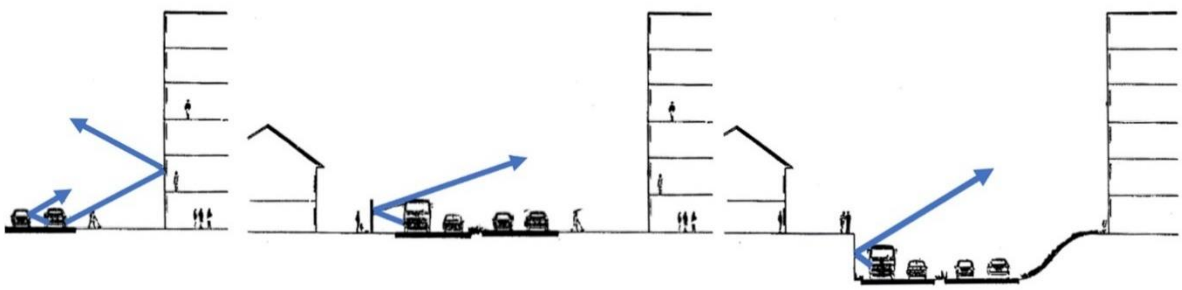


Figure 6: Simple reflection on an infinite flat surface, *sound source* **S** *and virtual image source* **S'** [15]

When a single sound wave, emitted by a source **S,** hits a hard flat surface (see Figure 6), it reflects on it “as if” a virtual *image source* **S'**, symmetric to the original sound source **S** with respect to the surface, radiated behind this surface and redirected the incident sound wave.

We then speak of "specular" reflections: any incident ray is reflected in a "specular" way, so that the reflected ray is redirected with an angle that is identical to the one at which it arrived on the surface.

Practically, reflections enhance the energy in the zone facing the surface/noise barrier. They can increase the noise (up to + 3 dB) in possibly noise sensitive zones that would have been less impacted if those reflections did not exist. Figure 7 shows examples of such *simple reflections*.



On vehicles/façades On a noise barrier On a sustaining wall

Figure 7: Examples of *simple reflections* [15]

To reduce the possible negative effects of *sound reflections* on noise barriers, *sound-absorbing* materials are widely used in EU.

However, *inclined sound reflecting* noise barriers are sometimes used instead of *vertical sound-absorbing* noise barriers - the idea being to send the reflected waves to non-sensitive zones (so to say: *to the sky*). This is forgetting that, due to weather phenomena, the energy might be *spread everywhere* and still going towards *sound sensitive* zones (see Figure 8).

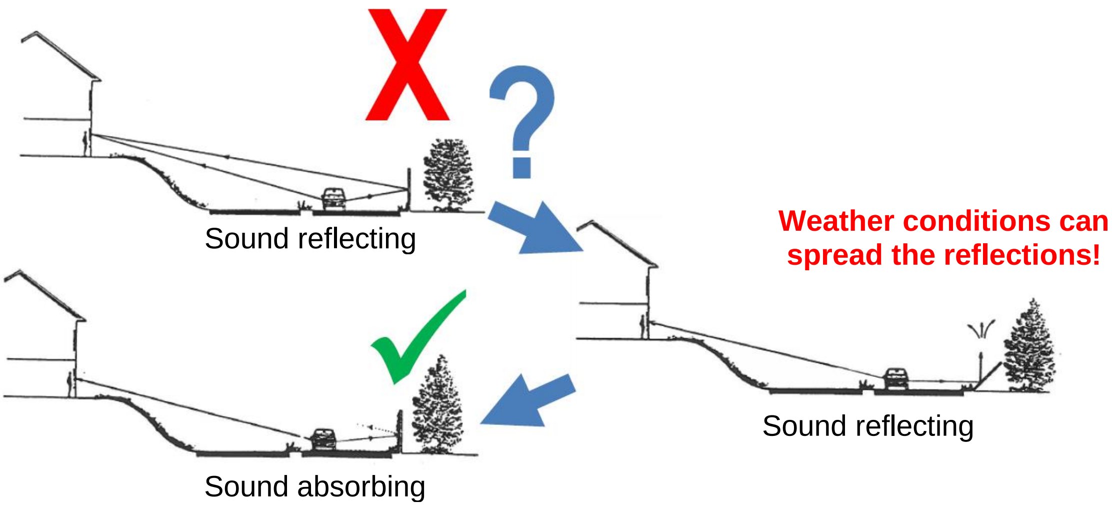


Figure 8: *Sound-reflecting* noise barriers do not dissipate the energy: *sound-absorbing* barriers do [15]

Sound-absorbing noise barriers are definitively the best ones to dissipate the incident energy as soon as it hits the noise barriers surface.

Multiple sound reflections

The effect of simple reflections is already important for the noise barrier performance, but multiple reflections can worsen the situation even more.

Multiple sound reflections occur when two walls are facing each other. This situation is very unfavourable because the sound waves are continuously reflected from one wall to the other, as in a "ping-pong" game, see Figure 9.

Figure 9 shows three examples of parallel surfaces in urban environment: between building façades, between parallel noise barriers and between sustaining walls. The third example is an open-air trench of 2 x 2 lanes width and 6 m height: in this case, the corresponding *noise performance* could be enhanced by more than 8 dB(A) thanks to *sound absorbing* materials.

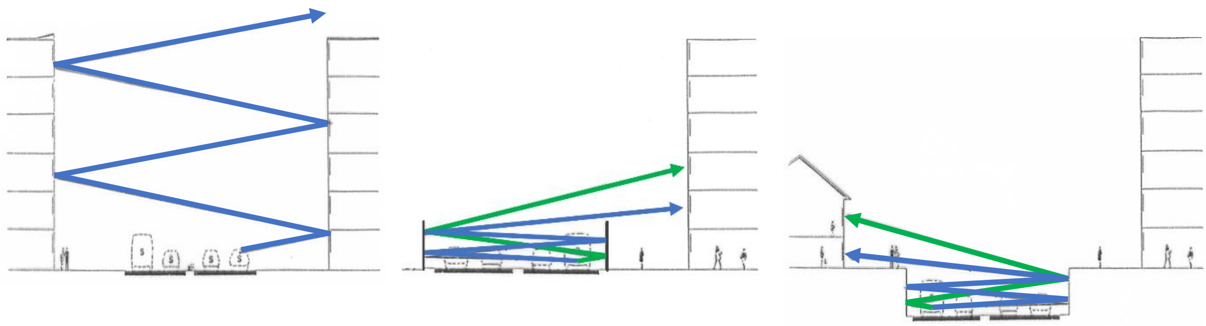


Figure 9: Examples of *multiple reflections* [15]

Sound-absorbing noise barriers (as well as sound-absorbing claddings) are even more efficient to reduce noise wherever multiple reflections occur.

Finally, while parallel noise barriers or parallel side walls induce multiple reflections in one direction (walls to walls), one can also have two directional multiple reflections within tunnels (between walls, road and ceiling). Again, sound-absorbing materials will significantly reduce reflections and the corresponding noise propagation to the environment, but this specific case is not part of this guidelines.

Interactions with the vehicle bodies

Multiple reflections can also occur between noise barriers or close walls and the bodies of vehicles passing in front of them: indeed, if vehicles can (in broad lines) be assimilated to *point* noise sources, at least for receivers at a certain distance from them, they are *real volumes* moving on the road, *volumes* whose sides (the vehicle bodies) are also *sound-reflecting* [15] .

In that way, interactions take place between the *sound-reflecting* noise barriers or close walls and the vehicles when they face each other. It is therefore also a similar phenomenon of *multiple reflections*, but here with a very specific *temporal dimension* (the effects "follow" the vehicle as it travels in front of the noise barriers). Figure 10 shows this interaction effect.

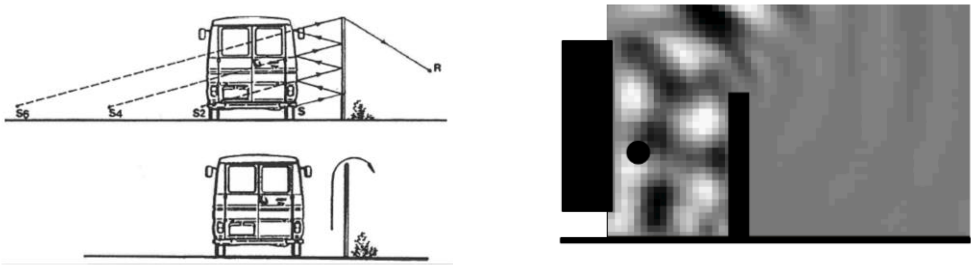


Figure 10: Interactions between a vehicle and a sound-reflecting noise barrier [15]
In the right image the vehicle body is represented by the black rectangle.
The final effect is as if the noise source was artificially raised up to the top of the barrier.

Thus, by artificially "raising" the height of the noise source, interactions significantly reduce the protective effect of the noise barriers. This effect is even worse if the vehicles are tall (artificial raise of the sound source) and long (increase of the effect duration): unfortunately, the tallest and longest vehicles are the noisiest vehicles on the road[5], namely trucks.

To reduce the effect of multiple reflections and interactions, the use of sound-absorbing materials is recommended Their effectiveness in reducing the additional noise will, however, vary depending on the vehicle pass-by: even if sound-reflecting noise barriers could reduce noise on the entire vehicle pass-by (L_{Aeq}), they sometimes increase the instantaneous noise (compared to the free field situation without any noise barriers) when the interactions are the strongest (in particular affecting L_{Amax}) [15] . In such situations, one can easily understand why some neighbours might complain they suffer an increase of noise (in fact, an increase of the L_{Amax}), although the L_{Aeq} is effectively reduced thanks to the noise barrier.

Conclusions on sound reflections

The effect of sound reflections on noise barriers strongly depends on the context:

- on wide highways with noise barriers placed quite far away from the closest traffic lane, one clearly understands that the effect of reflections is negligible,
- sound reflections are the most important when noise barriers are close to the traffic lanes (the closest ones usually supporting long and high bodied trucks), or close to trams or trains[5], or with narrower roads as highway ramps: in such unfavourable cases, it is hardly acceptable to recommend sound reflecting noise barriers that could even increase the already high existing *maximum* noise levels (L_{Amax}),
- In between those two extremes, the effect of reflections can go from 0 to 6 dB.

This is the reason why, with the exception of visually transparent and therefore sound-reflecting noise barriers, the most used noise barriers in EU are sound-absorbing ones.

[5] For railways, the effect of interactions is even worse: the succession of carriages results in a *long* and *continuous sound-reflecting* body.

2.1.2.2 Sound Diffraction

In the *optic* domain, placing an obstacle of usual dimensions in front of a source of light creates a *shadow zone*. In the *acoustic* domain, placing an obstacle between a source of noise and our ears does not prevent us from continuing to hear the noise. The reason is that, at audible frequencies, *sound wavelengths* are comparable to the dimensions of the obstacle: the energy *diffracts* on its edges, which re-propagates it in all directions, including behind it; this is s*ound diffraction*.

Figure 11 shows a simplified animation of the sound diffraction effects over a straight reflecting obstacle. It includes thus the reflected wave toward the side of the noise source: the wave "passes" to the other side of the obstacle, while being attenuated. One understands how a wavefront of the same order of magnitude as the noise barriers (few metres) literally "passes over" the top of the barrier to reach the *shadow zone*[6] and the people living there.

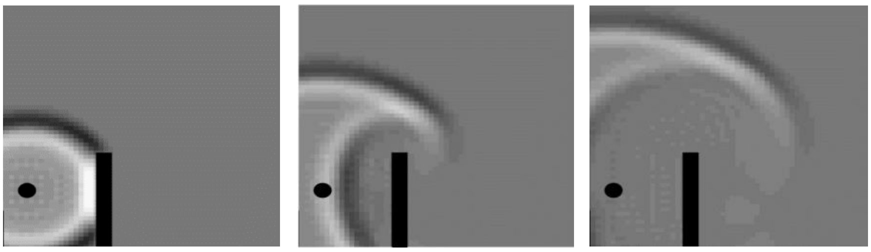
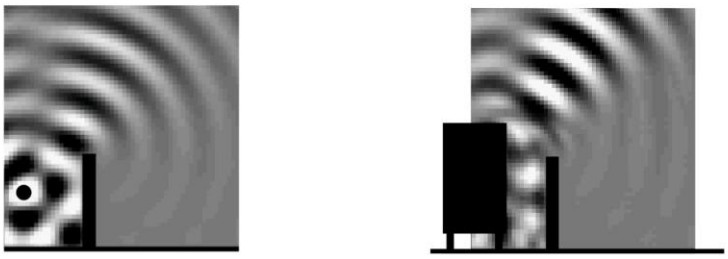


Figure 11: Propagation of a wavefront on a reflecting obstacle [15]

This simple example considered only a single wavefront and a single reflection on the obstacle. In reality, along a road/railway, the sound waves are continuously emitted by vehicles and there are also interactions with the ground on each side of the obstacle. Figure 12 presents an animation closer to reality: at the left, with a single point sound source, at the right with a high truck that involves interactions between its body and the barrier. As it occurs among traffic and noise barriers, sound diffraction is a very complex phenomenon, involving numerous sound waves from numerous moving vehicles at numerous locations.



simple point *sound source* *interactions* with a truck body

Figure 12: Propagation of continuous waves on reflecting obstacles as reflecting noise barriers [15]

<u>What is the best place for a noise barrier to be effective?</u>

The greater the shadow zone, the more effective the noise barrier (Figure 13).

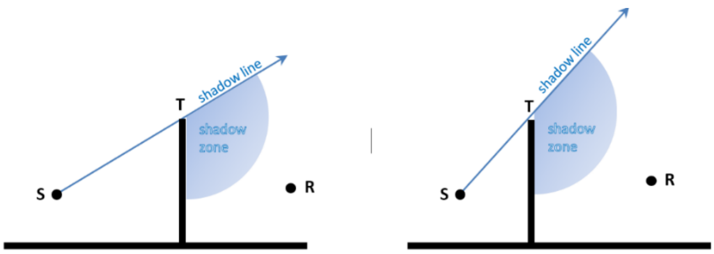


Figure 13: The closer the noise barriers to the source, the higher the shadow line, and the more efficient the noise barrier [15]

[6] *shadow zone*: zone located under the shadow line, joining the noise source to the top of the noise barriers.

However, a street, a road or a railway platform can have several traffic lanes or tracks. Some are therefore closer to the noise barriers, while some others more distant. With more distant traffic, the shadow lines are lower and lower, and the noise barriers becomes less and less performant to reduce noise on the protected side of the barrier (Figure 14).

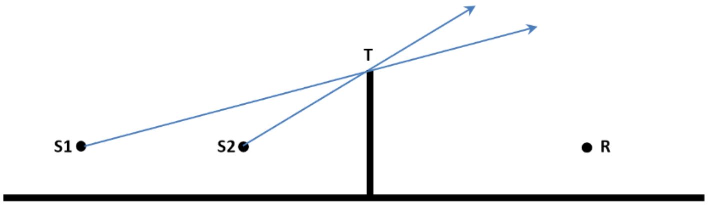


Figure 14: A noise barriers is less effective on the most distant noise sources [15]

Earth berms

Often naturally vegetated, earth berms can constitute obstacles to the propagation of traffic noise that are visually more appreciated than the "classic" noise barriers. However**, earth berms require a much larger footprint than a noise barrier of the same height**: this lowers the shadow line as shown in and consequently the performance (Figure 15).

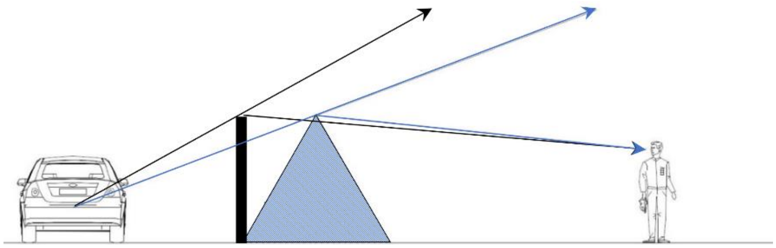


Figure 15: Earth berms: the footprint lowers the shadow line and then the noise reduction [15]

In addition, besides "lowering the shadow line", earth berms have two additional effects which also *reduce* their performance:

- instead of hitting a vertical obstacle, the wavefront "climbs" the obstacle along a slope that is easier to "overcome" than with a vertical noise barrier;
- at the top, the energy radiates within a smaller angle than for a "thin" screen and thus the sound pressure becomes higher

However, earth berms might have vegetation that could have interesting sound-absorbing characteristics and, consequently, could *enhance* their noise reduction performance.

When calculating the efficiency of an earth berm, it is important to never forget all those effects.

2.1.2.3 Airborne Sound Transmission

As shown at Figure 16, when a wavefront reaches the surface of the noise barrier, a certain part of the incident energy is reflected towards the "*unprotected" side* or absorbed depending of its *sound absorption* characteristics (2.1.2.1 Sound Reflection*).* The remaining part of this incident energy transmits through the barrier and then propagates to its "protected side": this is referred to as *airborne*[7] sound transmission. Finally, the wavefront reaches the top of the barrier, diffracts on it and then propagates to the "protected" side (0 Sound Diffraction).

[7] *"airborne"* (transmission via the air) is used to differentiate it from the so-called *"ground borne"* (transmission via the ground) transmission that could happen between the vehicles and the surroundings through the ground and finally radiates inside the buildings: *ground borne* transmission can be rather important for railways.

The noise perceived behind the noise barrier corresponds to the sum of the energy transmitted through it AND the energy diffracted at its top:

Figure 16: *Noise perceived behind the noise barrier = transmitted noise "+" diffracted noise* [15]

To obtain the best possible performance, the noise transmitted through the barrier must be *negligible* compared to that one diffracting at its top, the following *rule of thumb* applies:

The effect of sound transmission is negligible (≈ 0.1 dB) if the single-number rating of airborne sound insulation DL_{SI} is 15 dB[8] higher than the target performance ΔL_{Aeq} *(the one which would theoretically be obtained only by diffraction):* $\boldsymbol{DL_{SI} > \Delta L_{Aeq} + 15\ \mathrm{dB}}$.

Figure 17 shows the effective *practical performance* of a noise barrier with a targeted *theoretical* performance of 8 dB by *sound diffraction* only when sound transmission occurs as a function of its *airborne sound insulation* performance. It also shows that in this particular case it is not necessary to require more than [8 + 15 =] 23 dB of sound insulation because, beyond this level of performance, the transmitted energy becomes sufficiently negligible: **with a theoretical performance of ΔL_{Aeq} = 8 dB** by *diffraction* only, **a barrier with DL_{SI} = 23 dB will perform as well as one with DL_{SI} = 50 dB**.

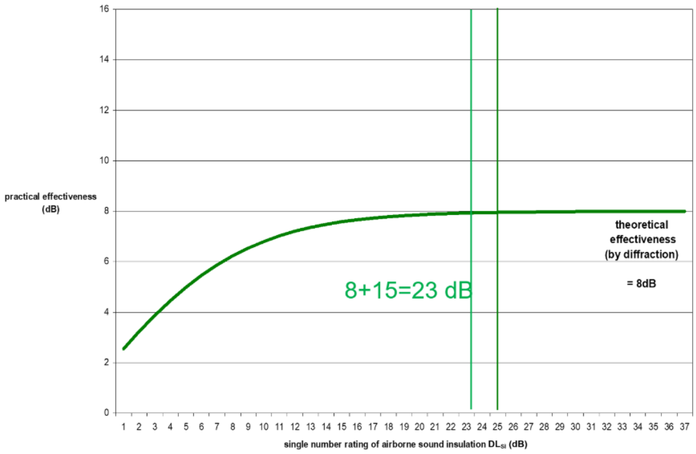


Figure 17: Effect of *airborne sound transmission* on a NB with total performance of ΔL_{Aeq} = 8 dB[15]

Traffic noise remains definitely a *time-related phenomenon* that occurs at any single vehicle pass-by: even if the most common unit used to characterise traffic noise is the *equivalent sound level* $L_{Aeq,T}$, to establish relevant values for the *airborne sound transmission*, it is necessary to consider its *effect on the instantaneous noise levels* $L_A(t)$ instead of $L_{Aeq,T}$.

Figure 18 and Figure 19 (next page) show instantaneous noise levels $L_A(t)$ when a 4 m high truck passes in front of a 2 m high and a 7 m high noise barrier, respectively:

- black curves present the pass-by noise level in free field, i.e. without any noise barrier,
- green curves present the pass-by noise level due to *pure sound diffraction*.

The difference between the black and green curves represents the noise reduction effect due to *pure sound diffraction* in function of the position of the vehicle: for a 2 m high barrier, it goes from 7 dB (far away) up to 15 dB (vehicle just behind the barrier).

[8] Some NRAs use + *10 dB* instead of + *15 dB*: then, transmission decreases the IL by 0,4 dB instead of 0,1 dB.

We purposely consider an *airborne sound insulation performance* DL_{SI} of 20 dB (a bit lower than [7 + 15 =] 22 dB).

- violet curves present the pass-by noise level due to *pure sound transmission*,
- orange curves present the total effect of *pure sound diffraction + pure sound transmission*.

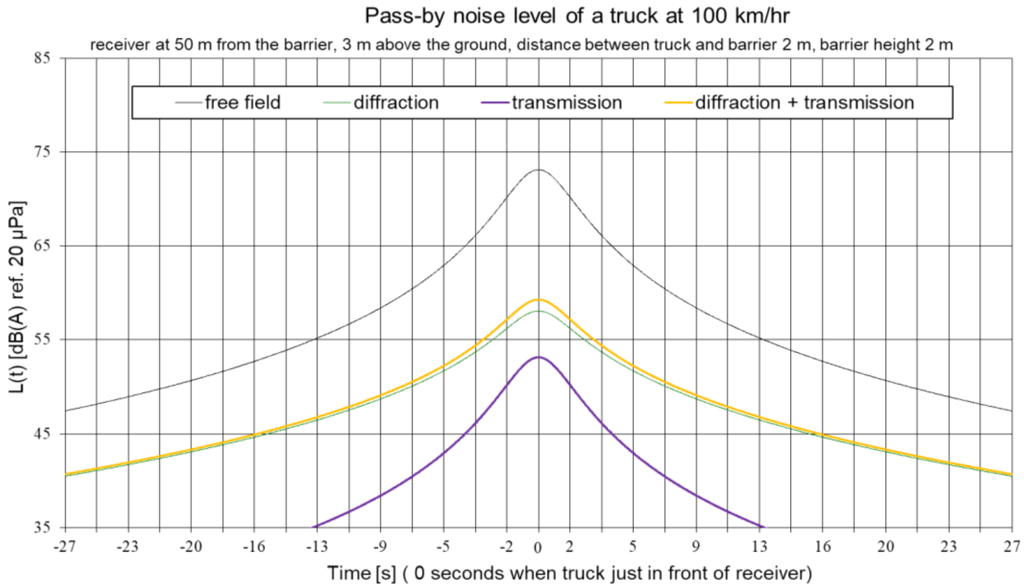


Figure 18: Effect of *airborne sound transmission* (DL_{SI} = 20 dB) on total performance of a 2m high NB

Already with a 2 m high barrier, *airborne sound transmission* can degrade the noise reduction. *Sound transmission* has a negligible effect when the vehicle is far away but becomes significant when the vehicle passes in front. With a 7 m high barrier, *airborne sound transmission* can now degrade the targeted noise reduction on the highest noise levels by more than 6 dB when using a barrier with DL_{SI} of 20 dB: in that case, a DL_{SI} of about 35 dB is appropriate.

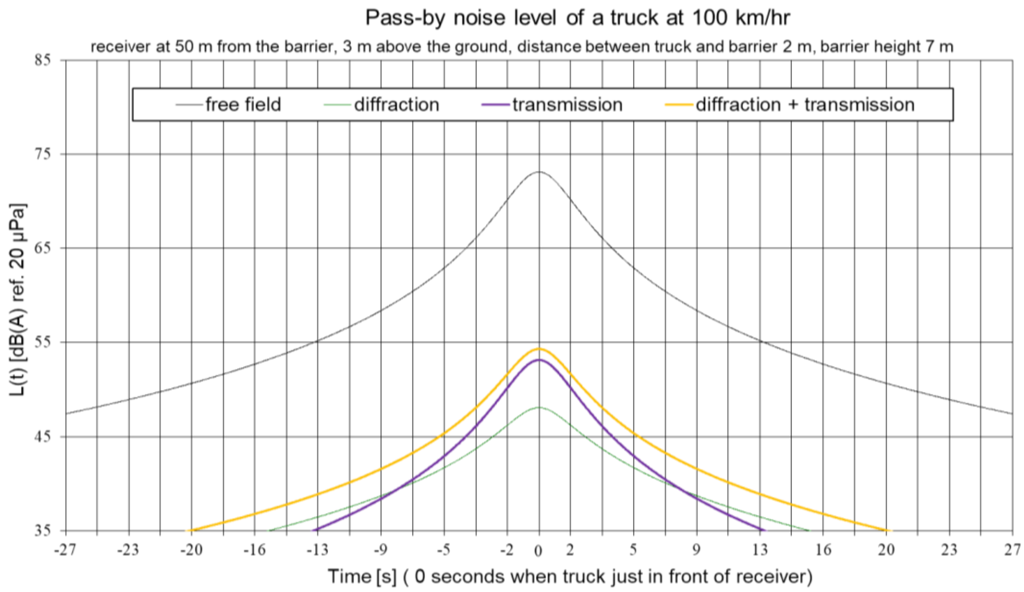


Figure 19: Effect of airborne sound transmission (DL_{SI} = 20 dB) on total performance of a 7m high NB

***Sound transmission* is an important characteristic: the performance to achieve is a function of the targeted performance on the highest pass-by noise levels. However, higher values are useless as they will give no further improvement to the total acoustic performance of the noise barrier.**

2.1.3 The Emission Characteristics

Before approaching the noise barrier, *sound waves* are first *emitted*: as *sound propagation*, *sound emission* plays an important role in the noise barrier performance to reduce noise.

At the early stages of *traffic noise control engineering*, it was common to model vehicles as *point sound sources* for road vehicles and *finite length line sound sources* for trains. However, road vehicles are no *point sound sources*, and trains are no *finite length line sound sources*. They do have characteristic *sound directivity*. *Directivity* governs how the energy reaches the noise barriers. Figure 20 shows examples of directivity patterns for passenger cars, light trucks, and heavy trucks, while Figure 21 shows examples for trains. *Directivity* partly explains why noise barriers could better reduce railway traffic noise than road traffic noise: being placed where the trains/trams radiate their maximum energy, “low-height” barriers make full use of this effect.

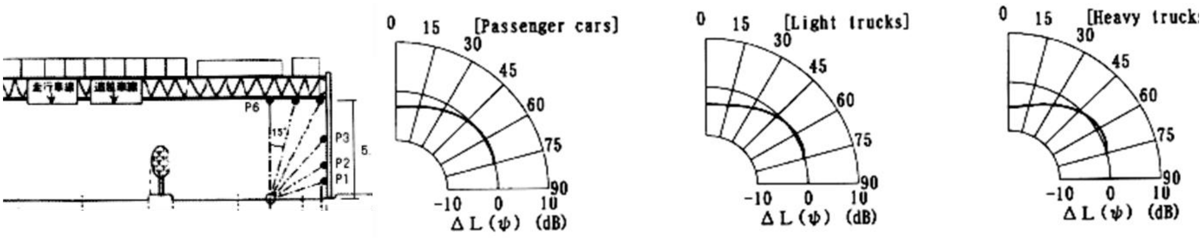


Figure 20: Examples of *sound source directivity patterns* of road vehicles [15]

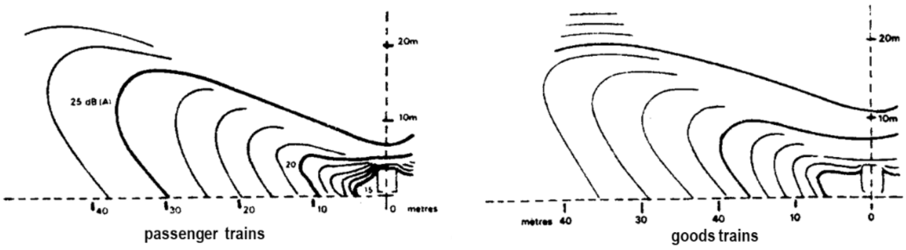


Figure 21: Examples of *sound source directivity* patterns of trains [15]

2.1.4 The Dimensions

2.1.4.1 *Geometric* dimensions of the objects

All the objects involved in the traffic noise, from the noise emission up to its perception, do have geometric dimensions that influence the noise reduction performance of noise barriers.

Vehicles dimensions

Every single vehicle is a *moving volume* with *sound reflecting* surfaces delimiting its body, some vehicles being possibly quite long as trucks and trains: those dimensions do influence the performance of noise barriers and should be considered when evaluating it.

Obstacles dimensions

Chapter 0 Sound Diffraction detailed the logic effect of noise barrier **height** in their *noise reduction* performance, while Chapter 2.1.3 hereabove states that a *limited height* noise barrier could still be efficient if placed in the area where the greater part of the sound energy is radiated, as *low-height noise barrier* for trams or trains. Apart height, the noise barrier **length** is also important: not only because a *finite length* noise barrier might not hide some parts of the traffic, but also because even on the hidden parts of the traffic, the lateral edges of the noise barrier also diffract the *sound energy* in the same way the top edge does (0).

Figure 22 shows *noise maps* around a four lanes/tracks traffic situation drawn at a height of 4 m above a full flat environment protected by a *perfectly sound-absorbing* 3 m high barrier: with an *infinite length* barrier *with "no hole"* and *with a "hole"* of 50 m, then a finite length barrier of 500 m length, and a barrier with two sections of 225 m length, separated by 50 m.
Figure 22 clearly shows how negative the noise coming from the unshielded sections can be while those effects can even be worsened by the wind / weather conditions.

infinitely long
3 m high barrier

infinitely long
3 m high barrier
with "hole" of 50 m length

500 m long and
3 m high barrier

2 sections of 225 m long
and 3 m high barriers

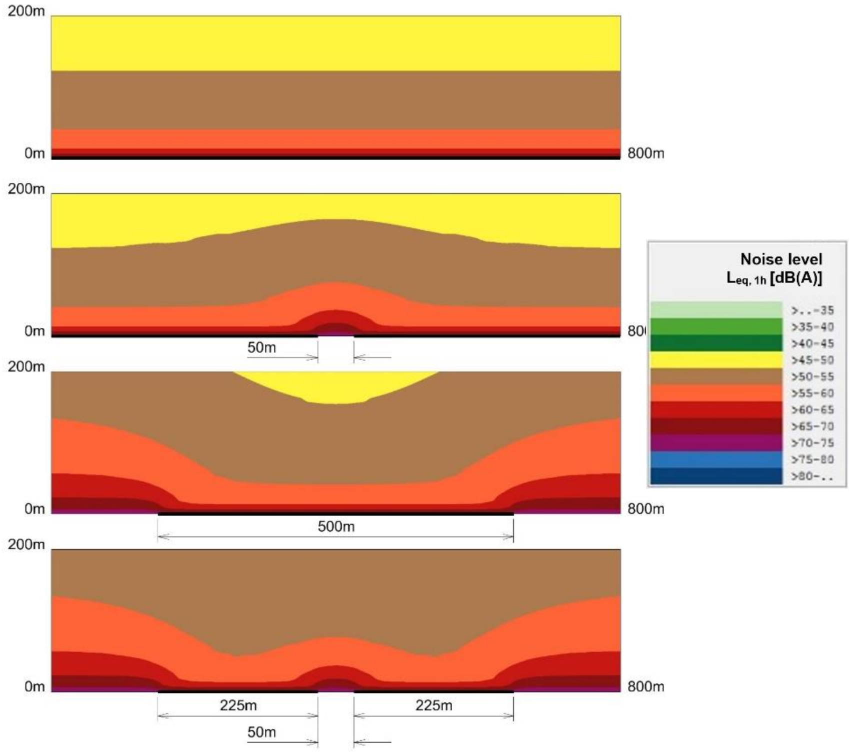


Figure 22: Noise maps showing the effect of noise barrier length [15]

Figure 22 shows the effect of different barrier lengths by $L_{Aeq,1h}$ *noise maps*, while traffic noise remains a time-related effect. For a single vehicle pass-by, one can easily understand how such pass-by noise levels can be negatively perceived when the vehicle passes in front of any unshielded section that could exist in *finite length* noise barriers.

Numerous surveys advice about the importance of noise barriers heights and lengths, as [25].

Finally, noise barriers are most often considered as "*thin*" obstacles: this is the case with most noise barriers. However, some might be *quite big*, and then their **volume** can also influence the *noise reduction* performance. On the EU market, noise barriers are not always *thin*, *flat* and *vertical*: more and more *products* are *volumetric* and/or *non-flat* and/or *non-vertical* (e.g. *vegetated* barriers, *gabions*, particular *shaped* barriers). Their effects on noise reduction could be rather complex and difficult to calculate, what explains why it is too often neglected.

2.1.4.2 Sound source / noise barrier / receiver *relative positions*: topography and infrastructure profile

The *relative position* of the *sound sources* (vehicles), the obstacles to the *sound propagation* (noise barriers) and the receivers (pedestrians, dwellings) conditions the *sound attenuation* due to *sound diffraction* of noise barriers: the more inclined the shadow line relative to every single vehicle, the greater the *sound attenuation* (Figure 13). Thus, by playing on the inclination of the shadow lines, the topography surrounding the traffic infrastructure, as well as its longitudinal profile will also strongly influence the *sound propagation*: they can even create natural obstacles to *sound propagation* (see Figure 23 and Figure 24).

Excavated roads / platforms - Surface roads / platforms - Elevated roads / platforms: without noise barriers

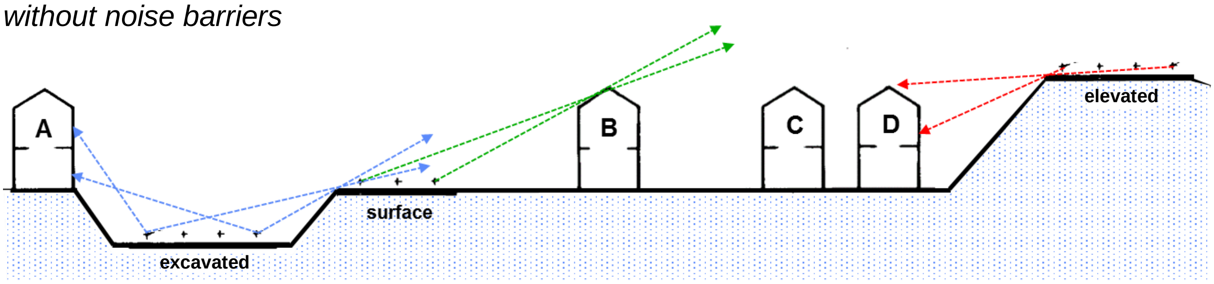


Figure 23: How longitudinal profile and topography influence *sound propagation without noise barrier*

In the example, for the sake of simplicity, four rows of one floor houses are considered.

Without noise barrier, the higher the road/platform, the larger the noise impacted area:

- Excavated or trench roads/platforms of medium depth (i.e.: approximately 5 to 7 m) can provide some protection on buildings which do not have a direct view on traffic;
- Buildings on the front rows of houses are very exposed but, if they are juxtaposed, they protect their own *back* façades (*quiet* façades) as well as the rows of houses behind.
- Unprotected elevated roads/platforms have the worst impact in urban areas.

Excavated roads / platforms - Surface roads / platforms - Elevated roads / platforms: with noise barriers

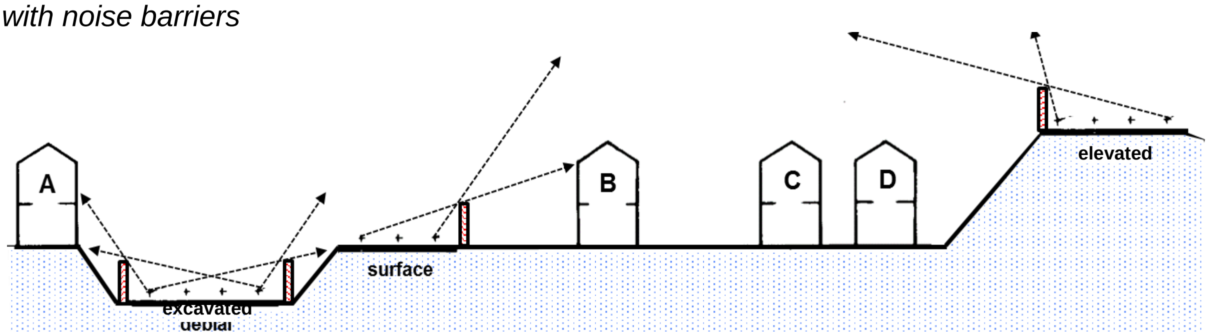


Figure 24: How longitudinal profile and topography influence *sound propagation with noise barriers*

With noise barriers, Figure 24 shows how the shadow lines are higher (and consequently the *sound attenuation*) when the infrastructure is higher compared to the houses to protect.

With noise barriers, the higher the road, the greater the noise reduction:

- Placing noise barriers at the bottom edge of *excavated* roads is *inefficient*;
- Placing noise barrier at the top edge of *trenches* or at the top of *excavated* roads, when possible, could be effective, except for floors with direct view on the road (even a partial view of some of the traffic lanes is enough to make ineffective the noise barrier);
- In *surface* situations, it is almost impossible to place noise barriers, except to protect urban spaces (e.g.: parks, sidewalks…), or if the houses to protect are sufficiently away from the road / train platform to be down in the *shadow zone*;
- noise barrier on elevated roads / platforms or viaducts are the most effective because they clearly raise up the shadow line.

In urban situations, *unprotected* elevated roads/platforms or viaducts are the "*worst*" cases of *noise pollution* and excavated roads the "*best*" ones.

However, when using noise barriers, protected elevated roads/platforms or viaducts are situations that offer the best *noise reduction* performance the barrier can have.

2.1.4.3 Frequency domain

The *wavelength* also plays a major role in the traffic *noise reduction*: they condition all the physical phenomena as well as the noise barrier *intrinsic* characteristics (see Figure 25): **the larger the *wavelength*, the worse its effect on the *noise reduction***.

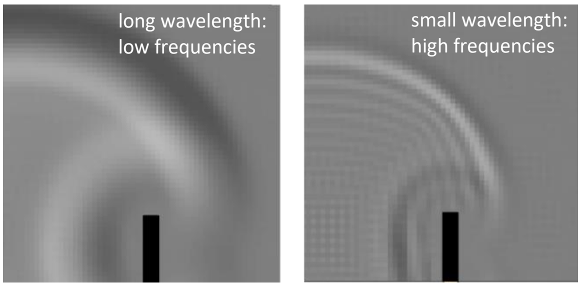


Figure 25: *Wavelengths* influence the noise barrier *sound attenuation* by *sound diffraction*

On the other hand, *road traffic noise* has a different frequency spectrum than *railway noise*: EN 1793-3 [4] defines the normalized *road traffic* noise spectrum, while EN 16272-3-1 [7] and EN 16272-3-2 [8] define the normalized *railway traffic noise* (Figure 26): with more energy in high frequencies (small wavelengths), noise barriers are more effective on railway noise.

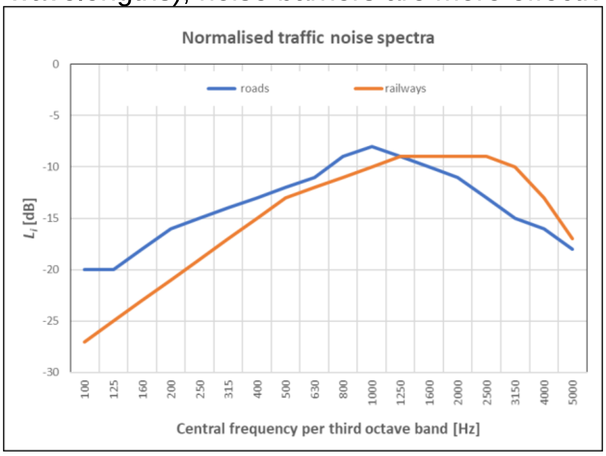


Figure 26: Normalised *road traffic* noise [4] and normalised *railway traffic* noise [7] spectra

2.1.4.4 Time domain

The *overall noise* perceived in the environment is nothing else than the sum of the respective contributions of every single vehicle moving at its own speed in the middle of the traffic: the *noise reduction* performance of a barrier is different for every single vehicle, depending on its kind, its position at a given time, not forgetting its relative level to the *background noise*.

The *time dimension* explains particular discomfort with isolated vehicles pass-by, as trucks perceived during quieter periods of the night due to weak airborne sound insulation (Figure 19), or *noise increase* due to multiple interactions with reflecting noise barriers (Figure 10).

2.1.4.5 The shape of the objects

The *shape of the objects* strongly influences the way the waves will be reflected on them, and it also influences the way these objects can diffract the *incident waves*.

Furthermore, as several objects can face each other, resulting effects of *multiple reflections* can accumulate: this can happen between two facing surfaces, whatever they are both *fixed* (two parallel sustaining walls or two parallel noise barriers), or *mobile* (two vehicles), or with one of the two being *fixed* (a retaining wall / a NB) and the other is *mobile* (a vehicle).

Vehicles

Bikes, cars, vans, light trucks, heavy trucks (semi-trailers and trailers), single length, double length or even triple length buses, trams, passenger trains, good trains each has a more or less *continuous body* of *different lengths*. *Sound waves* can thus be reflected in different ways, depending on the vehicle shape and length. In addition, when a single vehicle passes in front of a fixed receiver point, the pass-by duration depends not only on its speed, but also on its length.

Noise barriers

The noise barrier market is very large. However, it is usual to subdivide it into categories (remembering that they all can be *sound-absorbing* or *sound-reflecting*):

- *thin flat* noise barrier: vertical or inclined (towards the vehicles or the environment);
- *thin non-flat* noise barrier: curved or of a particular shape (see Figure 27 and Figure 28);
- *volumetric* noise barrier: vegetated barrier, “stepped” retaining walls;
- while they can also be capped with some *additional devices* (so-called *added devices*) intended to improve the *sound attenuation* obtained by *sound diffraction* on the noise barrier top edge (Figure 29).

In the early years of noise barriers, (*sound-reflecting*) ***thin flat inclined* noise barriers** were used to send *sound reflection*s away from inhabited areas. Figure 8 shows why vertical *sound-absorbing* noise barrier are better choices.

***Thin non-flat* noise barrier** are often designed to avoid problems of *sound reflections*/*multiple reflections*. Their design has to be adapted to the shape of the vehicles whose noise they have to reduce. Figure 27 shows a noise barrier *specially optimised* to enhance its *noise reduction* when protecting the noise propagation from a high-speed train.

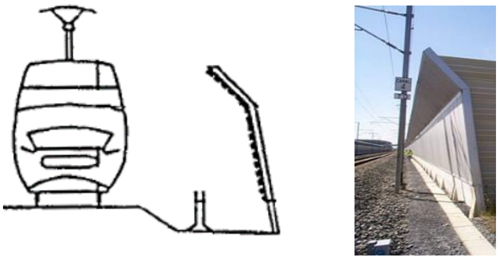


Figure 27: High-speed train with *special shaped body* facing an *optimised shaped* noise barrier (© A-Tech)

On viaducts, *visually transparent* noise barriers are often preferred because they reduce their visual impact. However, *visually transparent* materials are unfortunately *sound-reflecting* and, if they were placed vertically, they would also provide *multiple reflections* degrading their IL. Therefore, in order to better control these *multiple reflections*, curved shapes are often used: Figure 28 shows a visually transparent noise barrier that has been *curved* designed to reduce the negative effect of *sound reflections*.

Figure 28: *Sound reflecting* noise barriers curved to reduce the negative effect of *sound reflections*

***Volumetric* noise barrier** such as vegetated NB, or *staircase sustaining walls* must be used very carefully. In fact, their *sound absorption* characteristics can be limited depending on the design and often require a healthy vegetation, thus careful maintenance

The noise barrier product standard EN 14388 [1] defines an ***added device*** as:
"*additional component that influences the acoustic performance of the original noise-reducing device, acting primarily on the diffracted energy*" (e.g.: Figure 29).

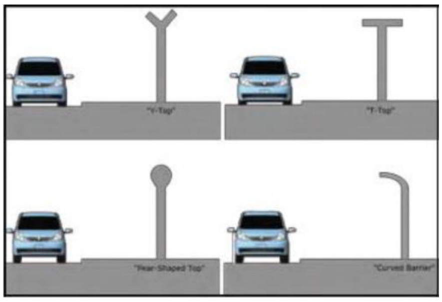


Figure 29: Different examples of added devices [9]

However, one must remain cautious about the alleged *increase of sound attenuation* of such devices. They are only effective *under* the shadow line and can, in no way, justify an equivalent reduction in height for dwellings looking over the corresponding lowered line (Figure 30).

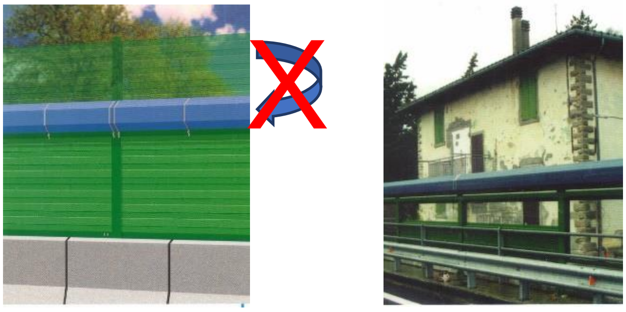


Figure 30: Use *added devices* carefully as they may not protect above the *shadow line*

2.1.5 The Sound Propagation Medium: Air / Weather Conditions

Sound waves cannot propagate without a *medium*: the air. Weather conditions[9] have a major influence on the *sound propagation* and, thus, on the *noise reduction* performance of noise barriers: this has to be taken into account when planning new noise barrier projects.
Modern calculation methods (e.g., CNOSSOS-EU) consider this effect based on yearly averaged weather conditions.

2.1.6 The Intrinsic Characteristics

Intrinsic characteristics are the ones inherent to the noise barrier elements and products themselves. Previous chapters (*2.1.2.1 Sound Reflection* and 2.1.2.3 *Airborne Sound Transmission*) have already shown how important those *intrinsic* characteristics can affect the global noise reduction of noise barriers. Chapter 3 of the Task 5.2 report within Deliverable 5.1 [15] explains this in detail.

It is thus important to consider the *intrinsic sound absorption* and *airborne sound insulation* already at the planning stage of new noise barriers projects (e.g. carefully choosing between *visually opaque* and *visually transparent* noise barriers, the last ones being possibly negative due to sound reflections if not correctly shaped).

[9] e.g., wind direction, wind speed, temperature and relative humidity

2.2 *Noise Barrier Design*

Before the installation of new noise barrier projects, after the planning stage, one must finalise their design. To be effective, the noise barrier projects must be carefully designed by experienced persons: at this stage, all the parameters that condition the performance of the projects have to be chosen and fixed in order to guarantee their final targeted noise reduction along their lifetime.

2.2.1 Main Parameters

Modern calculation methods and software are able to take into account the major factors (see chapter 2.1) that will lead to the noise reduction achievement. At the end of this dimensioning work, according to the targeted noise reduction, one should have fixed:

- The location of the noise barrier(s),
- The height and length of the noise barrier(s),
- The *intrinsic* characteristics (*sound absorption* and *airborne sound* insulation) that are necessary to achieve the performance.

2.2.2 Materials

Many manufactured products are now available on the European market to build up effective noise barriers. Good products can easily fit the usual performances for *intrinsic sound absorption* and *airborne sound* insulation. All those products can be made of one or different materials: as of today, one can say that, whatever the materials, *good manufacturers* do know how to design their product in order to guarantee their performance along their lifetime and following their *intended use*. In other words, it is not fair to say that a material is better or worse than another one, what is too often wrongly concluded based on bad experiences, themselves based on bad products. Of course, bad experiences and bad products must be kept as relevant of what to avoid, but one must let to the manufacturers the care to develop their own products in such a way those products could show performant and sustainable characteristics.

All the important *noise barrier product* characteristics, whatever they are *acoustic* or *non-acoustic,* are considered within the EN 14388[10] product standard [1] , this one referring to a list of supporting standards that refer themselves to the latest relevant testing methods for characterising the performances.

Also named *traffic noise reducing devices*, *noise barriers products* correspond to two main categories: the (visually) transparent ones, and the (visually) opaque ones.

2.2.2.1 Visually transparent noise barriers

Due to the material used, usual (visually) transparent products are *sound reflecting*. Common materials are: glass, polycarbonate and methacrylate. Once again, there is no “better” material than the other ones: when a material has some drawbacks, *good manufacturers* know how to design their product to take those drawbacks into account and counteract the problems accordingly, not only for their *airborne sound transmission*, but also for the other important characteristics we have not to forget and that are not related to acoustics: safety (danger of falling debris, transparency characteristics, shock sensitivity, glare…), durability and sustainability.

[10] At the date of this report (May 2022), the whole package of the product standard EN 14388 [1] and all its is supporting standards is under revision: the use of the latest supporting standards (referring to relevant and updated assessment methods) is always advised because the *effective performances* of the products, tested with the relevant methods, are more important than their *CE mark* (products can even be CE marked while having many NPD – *No Performance Determined* – values…). CE Marking is ruled by the *Harmonised standard* HEN 14388:2005 and must be done by an official Notified Body [21] .

2.2.2.2 Visually opaque noise barriers

On the other hand, (visually) opaque noise barriers could be either sound reflecting or sound absorbing.

As already pointed out, there is no "better" material than the other ones: when a material has some drawbacks, *good manufacturers* know how to design their product to take those drawbacks into account and counteract the problems accordingly, not only for their *acoustic* characteristics, but also for the other important *non-acoustic* ones as: safety, durability and sustainability.

The majority of the European noise barrier products correspond to the following materials:

- Concrete barriers,
- Metallic barriers,
- Wood barriers,
- Plastic barriers,

and, to a much lesser extent, Mineral wool, and

- Gabions.

All those noise barriers products have their own specific advantages and drawbacks that could be too long to discuss here. Table 2 (next page) presents *an attempt* to regroup the main characteristics of those products in function of their main "materials" categories, but one must be careful to conclude too quickly: the *quality* of a product does not depends on its materials, but on its design, its manufacturing process and its quality control.

It is left to the readers to choose one (or even several) materials that might be suitable for their own *intended use*, while choosing *products* well designed to fit their *intended use*.

2.2.3 European Noise Barrier Products Trends

Interesting outcomes of the state of art established under SOPRANOISE Task 5.3 within Deliverable 5.1 [15] are the trends on the today's use of noise barriers in the European market.

Even if limited to the eighteen countries having replied to the survey, interesting facts can be presented:

- The *sound absorbing noise barriers* market is quite broad: about 19 million of m², even if limited to those countries having replied.
  In total, the *concrete barriers* are predominant, then the *metallic ones (steel / aluminium)*, then the *wood ones*.
- Even if about 4 times lower than the *sound absorbing noise barriers* market, the *sound reflecting noise barriers* market is still important: about 4 million of m².
  Here, logically, the predominant *sound reflecting noise barriers* are the *transparent* ones, then come the *concrete noise barriers* and the *wood noise barriers*, the other categories being negligible. Austria, Bulgaria and Finland stated that they are not working with *sound reflecting barriers on their network.*
- Table 1 hereafter summarises the proportions of sound absorbing, some reflecting and "other" noise barriers the survey established:

Table 1: statistics on the whole replies about NB types

absorbing (m²)	reflecting (m²)	other (m²)
18.841.897	4.221.274	1.723.954
76%	17%	7%
24.787.124		

Table 2 : advantages and drawbacks of main European noise barriers manufactured products in function of their materials categories

Concrete		Metallic (steel and aluminium)		Wood		Plastic		Mineral wool		Gabions	
+	caution	+	caution	+	caution	+	caution	+	caution	+	caution
Inert, strong, resistant	Heavy, Implementation	Light, strong, resistant	steel protection (corrosion)	"Living" material	"Living" material	Light, strong, resistant	Manufacturing with toxic products	Lightweight	Resistance	Inert, "natural" material	Acoustic performances ?
Possibility of freestanding elements	Fragile absorbent elements	Easy installation	Perforated steel KO	Appreciated natural appearance	Toxic fungicide treatment	Easy installation	UV resistance	Easy installation	Stackability		Fragile absorbent elements
Low maintenance	Absorbent elements maintenance ?	Easy maintenance	Perforated Aluminium OK	Various shapes	Dull and changing colors	Easy maintenance	Resistance to fire	Easy maintenance / replacement	Durability ?	Limited maintenance	Absorbent elements maintenance ?
Shapes	Limited colors	Shapes & colors	Absorbing material protection		Absorbing material protection	Shapes & colors, anti graffiti	Absorbing material protection	Possibility of climbing plants	Colors	Choice of materials, appearance	Limited colors
Anti graffiti smooth elements	Anti graffiti porous elements	Anti graffiti				Recycled plastics / recyclable ..			Weak anti graffiti	Anti graffiti reflective elements	Anti graffiti porous elements

2.3 Noise Barrier Procurement

The last step before installation is the noise barrier procurement requirements.

In order to ensure a sustainable and performant noise barrier project, authorities must require clear and certified performances against all the characteristics relevant to its intended use within the ones listed in the EN 14388 product standard[10] [1] .

2.3.1 Relevant Characteristics

EN 14388 product standard [1] lists the relevant characteristics for road traffic noise reducing devices (thus not only for noise barriers but also for claddings and for added devices):

For acoustic characteristics:

- (Sound absorption in diffuse sound field conditions[11]),
- (Airborne sound insulation in diffuse sound field conditions[11]),
- Sound absorption/reflection in direct sound field conditions, i.e. for noise barriers,
- Airborne sound insulation in direct sound field conditions, i.e. for noise barriers,
- (Intrinsic sound diffraction: only applicable for added devices[11]).

For non-acoustic characteristics (again outside SOPRANOISE (*acoustic*) field of application, but stated here as non-acoustic characteristics are important in noise barriers procurement):

- Reaction to fire
- Release of dangerous substances
- Resistance to wind loads and loads from passing vehicles
- Resistance to loads under self-weight
- Substitute load due to dynamic actions from snow clearance
- Resistance to dynamic loads from impact of stones
- Resistance to dynamic loads: risk of falling debris
- Safety in collision
- Safety in case of brushwood fire
- Light Reflection
- Static Transparency and/or Dynamic Transparency
- Long-term performance

While the *acoustic* characteristics have *always* to be specified, their values logically depend on the conclusions of the *design* survey.

Regarding the non-acoustic characteristics, the values to be required also depend on the *intended use*[12]. Therefore, depending on the *intended use* and the barrier location (relative to the traffic and to the environment), some *should be* mandatory (e.g. Release of dangerous substances, Resistance to wind loads and loads from passing vehicles, Resistance to loads under self-weight), while others *could be* mandatory or not, (e.g. Reaction to fire, Substitute load due to dynamic actions from snow clearance, Resistance to dynamic loads from impact of stones, Resistance to dynamic loads: Risk of falling debris, Safety in collision, Safety in case of brushwood fire, Light reflection, Static Transparency and/or Dynamic Transparency).

Finally, the long-term performance should also be considered because the noise barriers lifetime can be drastically influenced by the *exposure* corresponding to their *intended use*, while authorities want to keep the barrier in performant conditions as long as possible.

Sustainability is another important topic to consider at the procurement: this will be discussed under 2.3.4.

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[11] outside SOPRANOISE field of application as non-applicable for (free-standing) noise barriers dealt here.

[12] e.g. sea salt atmosphere, dry sunny country, in middle of fields, on viaducts, with close proximity of pedestrians or dwellings, etc.

2.3.2 Acoustic Characteristics

2.3.2.1 Sound Absorption/Reflection

For noise barriers, **it is fundamental to require only products that are *certified*** following the corresponding EN 1793-5 [5] .

On the one hand, the SOPRANOISE database of the acoustic characteristics of European noise barriers, established under Task 2.2 within Deliverable 2.2 [11] , allows a better understanding of existing manufactured products (Figure 31): the median value of the single-number DL_{RI} [13] over all test reports is 6 dB.

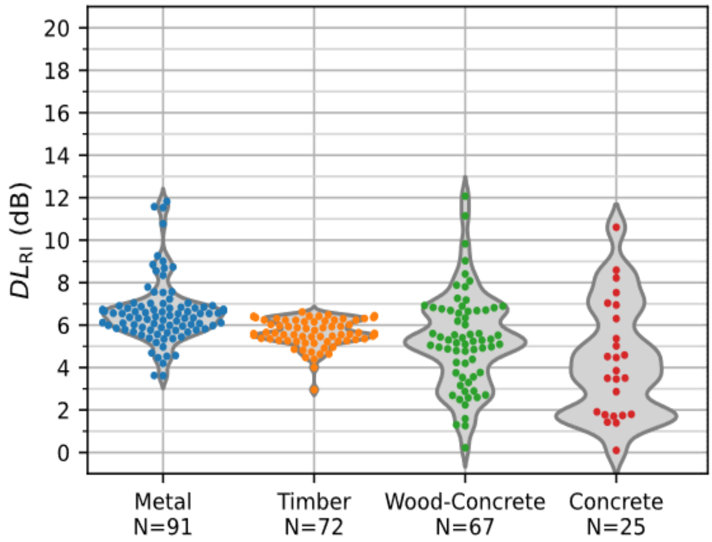

Figure 31: Single-number values DL_{RI} for all the test reports within the SOPRANOISE database [11]

On the other hand, the state of art on today's NB use in European countries, established under SOPRANOISE Task 5.3 within Deliverable 5.1 [15] , shows that the most *common* values the authorities are requiring within their specifications are: *DL_{RI} = 5 to 6 dB*, what is quite in agreement with the SOPRANOISE database.

When requiring minimal values for DL_{RI}, the higher the performance, the better the result. There is an asymptotic behaviour similar to the one shown at Figure 17 except that, here, we "add" the noise reflections to the noise directly radiated by the vehicles… While all the other factors (e.g. relative position vehicles / NB, ...) also rule the minimal DL_{RI} over which reflections could be considered as negligible or not (i.e. not significantly reducing the IL).

The correct value to require always depends on the parameters resulting from the *design* study (2.2.1). NRAs have the choice around many EU products that can achieve DL_{RI} = 5 to 6 dB or even higher. Whatever the values requested, it is highly recommended to write in the specifications that the **respect of the required values will be officially checked in-situ** (following the EN 1793-5 [5] standard) **directly after the installation (Noise Barrier Approval)**, but also possibly during the noise barrier lifetime (Noise Barrier Monitoring)[14].

Official rules about how to manage non-conform products should be also clearly stated in the specifications, while, indeed, the SOPRANOISE 3-step approach is a very useful way to assess the DL_{RI} of barriers all along their lifetime, as explained in the coming chapters : **2. Before Noise Barrier Installation**, **3. At Noise Barrier Installation**, **4. During Noise Barrier Lifetime** and **5. At Noise Barrier End of Life**.

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13 In some more sensitive cases, 1/3rd octave band spectral performance could be preferred to the single-number DL_{RI}

14 By the way, those mentions will never oblige any NRA to *do* the checks, but do inform the contractor about the *possibility to be checked*…

2.3.2.2 Airborne Sound Insulation

For noise barriers, **it is fundamental to require only products that are *certified*** following the corresponding EN 1793-6 [5] .

On the one hand, the SOPRANOISE database of the acoustic characteristics of European noise barriers, established under Task 2.2 within Deliverable 2.2 [11] , allows a better understanding of existing manufactured products (Figure 31): the median value of the single-number DL_{SI} [15] over all test reports for the elements is 34 dB (30 at posts and 31 for [posts + elements]: see [10]).

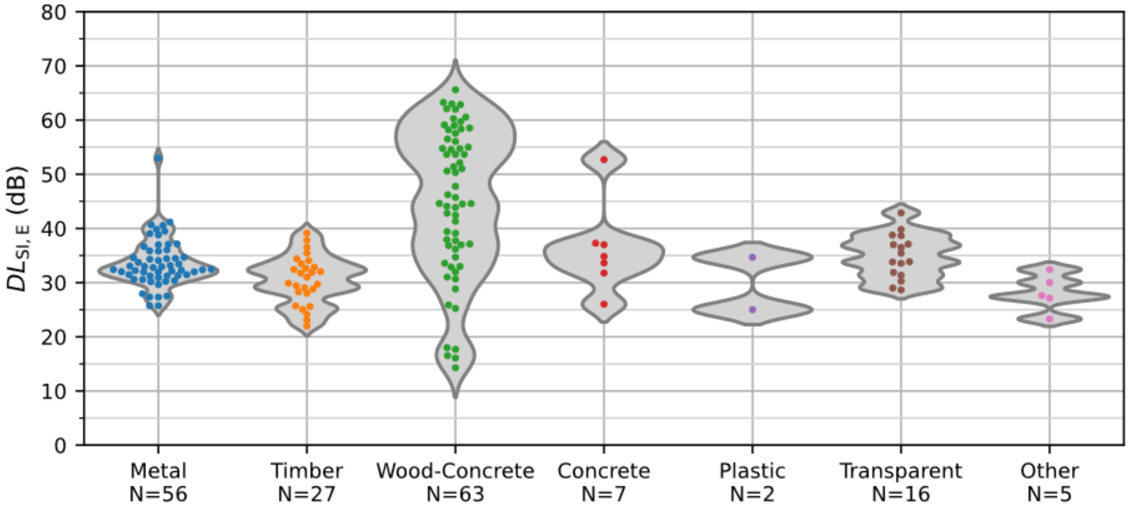

Figure 32: Single-number values DL_{SI} for all the test reports within the SOPRANOISE database [11]

On the other hand, the state of art on today's NB use in European countries, established under SOPRANOISE Task 5.3 within Deliverable 5.1 [15] , shows that the most *common* values the authorities are requiring within their specifications are in the range DL_{SI} *from 25 to 30 dB* (see Table 8 under 4.2.2 in [15] or further details for *elements*, at *post*, or for [*posts + elements*=] *global* values), what is quite in agreement with the SOPRANOISE database.

When requiring minimal values for DL_{SI}, the *simplest* rule is to refer at least to what explained in **2.1.2.3 Airborne Sound Transmission**: $\boldsymbol{DL_{SI}} > \Delta \boldsymbol{L_{Aeq}} + \boldsymbol{X}\ \mathbf{dB}$ where X depends on the *tolerated decrease* on the IL due to the energy transmitted through the barrier[16].

However, as for sound absorption, the correct value to require always depends on the parameters resulting from the *design* study (2.2.1).

Just remember that higher DL_{SI} do not improve the IL, as the sound transmitted through the barrier becomes quickly negligible in comparison with the diffracted wave (see Figure 17).

NRAs have the choice around many EU products that can achieve DL_{SI} > 28 dB[17]. Whatever the values requested, it is highly recommended to write in the specifications that the **respect of the required values will be officially checked in-situ** (following the EN 1793-6 [6] standard) **directly after the installation (Noise Barrier Approval)**, but also possibly during the noise barrier lifetime (Noise Barrier Monitoring)[18].

Official rules about how to manage non-conform products should be also clearly stated in the specifications.

As for DL_{RI}, the SOPRANOISE 3-step approach is also a very useful way to assess the DL_{SI} of noise barriers all along their lifetime.

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[15] In some more sensitive cases, 1/3rd octave band spectral performance could be preferred to the single-number DL_{RI}

[16] If *X = +10 dB,* transmission decreases the IL by 0,4 dB; if *X = +15 dB*, transmission decreases the IL by 0,1 dB.

[17] Note: DL_{SI} values are generally 3 to 5 dB higher than the previously used DL_R values

[18] By the way, those mentions will never oblige any NRA to *do* the checks, but do inform the contractor about the *possibility to be checked…*

2.3.3 Non-acoustic Characteristics Requirements

Non-acoustic characteristics requirements are outside the SOPRANOISE (acoustic) field of application and have not been investigated here. One can say that it is also very important to require adequate non-acoustic performances, while these depend much more on the site characteristics. Even if complex surveys could be done about those characteristics, trends will be very difficult to establish that could be used in common values to require.

2.3.4 Sustainability

Nowadays, the current dimension and the complexity of noise barrier projects confirm the need to apply the concept of sustainability for relevant construction work as well as for resources required to product, install, maintain, monitor and finally - if needed - to remove noise barriers once they have reached the end of their life cycle. This makes evident that noise barrier projects involve many resources (not only of the environmental type) and have in general a very high impact on the built environment as any other large built structure: *sustainability* should be considered in every new noise barrier project. With that objective, the TC226 WG6 group is currently preparing a new standard on sustainability: prEN17383 [22]

2.3.4.1 The Sustainability Approach

In general, the assessment of sustainability should be based on an ***environmental* Life Cycle Approach** taking into consideration cradle-to-cradle impacts, including resource impacts, long-term environmental performance (maintenance) and end of Life (decommissioning).

Social aspects should also be considered. i.e., transparency in the noise barrier is generally preferred by residentials as it helps to minimize the impact on the landscape; again, for noise barriers some materials are preferred to minimize heat island effect in the screened zone, use of earth berms to reduce the visual impact of barriers.

In parallel to the SOPRANOISE research, another CEDR research has been done about the way people react to noise: FAMOS (FActors MOderating people's Subjective reactions to noise). Especially, a *Guidebook on how to reduce noise annoyance* is now available [23] .

To assure a ***holistic* life cycle engineering approach,** the list of relevant aspects should be completed by adding different functionalities: security of supply, adaptability, lifespan extension options, high value recycling / reuse options, carbon capture capacity. Finally, noise barriers cost, and other **economic indicators** should also be considered.

Given this framework, **technical and functional** aspects represent the basis for further analysis of any possible overall sustainability assessment of a noise barrier, based on the calculation and / or the measurements of **(1) environmental**, **(2) social** and **(3) economic indicators**.

*A sufficient leve*l of performance with reference to the above requirements guarantees that the product meets functional and technical needs and represents the essential conditions for further investigations on a full set of Key Performance Indicators (KPIs) of the environmental, social, and economic for all different life stages. The Technical and Functional Design are necessary to be assured before an assessment of the environmental, economic, and social performances can be regarded meaningful or, to state otherwise: **sustainability cannot be achieved without a convincing Technical and Functional Design**.

The need for a Life Cycle Analysis (LCA) for noise barriers becomes also evident because of the large variety of materials and solutions (to some extent: already in use) which varies from the most classical options (concrete, metallic or wood cassettes) to the most recent ones (e.g.: cassettes in recycled PVC, sound absorbing natural fibers, gabions...). Moreover, innovative solutions for foundation works should be also considered. Roughly, one third of the total economic value of the noise barrier is represented by foundation works and alternative solutions, such as ground screws or metallic poles hammered (respectively drilled) into the ground, can be used instead of concrete curbs and ground cementation. The terrain remains untouched, there is no soil sealing and the overall logistical effort is reduced.

2.3.4.2 Sustainability and Green Public Procurement

Europe's National Road Authorities (NRAs) and railways infrastructure companies, which are in some case *public bodies,* and in other cases *private companies*, are the major *end users*, and operators of noise barriers. This increases the need for noise barrier sustainability to be considered by *all policy makers* and *all other relevant stakeholders* involved in the process, to be in line with a *growing sustainable agenda for surface transport* and its respective infrastructure. This need is covered by the European legislation on **Green Public Procurement** (**GPP**) as green purchasing criteria for **Road Design, Construction and Maintenance**, has been published[19]. Although GPP is a voluntary instrument, it has a key role to play in the EU's efforts to become a more resource-efficient economy and is a strong stimulus for innovation and for a more sustainable market: therefore, the GPP criteria[20] been applied more and more during the last years.

During the last decade, technical standards are also being developed to provide methods and criteria for supporting manufacturers when assessing noise barriers sustainability before placing the product on the European market: these standards must be considered within the scheme of technical standards used for drafting the Declaration of Performance (DoP) and applying the CE marking to noise barriers according to CPR (Regulation EU 305/2011).[21]

Finally, a general **scheme for all construction works** is offered by the standard EN 15804:2019 [20] , where a set of indicators is provided to assess sustainability over the entire life cycle. The results of the research project QUIESST[22] represent the first step into the topic of sustainability for the noise barrier sector: information can be drawn about a holistic approach to sustainability also including all evaluation criteria of the environmental, technical, social, and economic aspects.

2.3.4.3 The Sustainability Approach in the context of SOPRANOISE

The outcomes of the SOPRANOISE project should be evaluated in this context. Moreover, all possible benefits should be considered, having in mind how the new developed tools can help the sustainability assessment of noise barriers.

According to the SOPRANOISE 3-step approach: **(1) in-situ inspections, (2) in-situ "quick" measurements, and (3) in-situ "full" measurements** (EN 1793-5 [5] and EN 1793-6 [6] standards), the general idea is to assess the intrinsic acoustic performances of installed noise barriers from the easiest (but less accurate) way up to the most accurate one (but obviously related to more effort and costs).

The **in-situ inspections** (Step 1) and the **SOPRA measurement method** (Step 2) are big improvements that help a methodological assessment of noise barrier sustainability, when considering the following stages (with reference to the scheme taken from the standard EN 15804:2019 [20] :

- The Construction installation stage A5
- The Use Stages B1 to B5
- And the End-of-life stage C1.

[19] https://ec.europa.eu/environment/gpp/index_en.htm

[20] https://ec.europa.eu/environment/gpp/eu_gpp_criteria_en.htm

[21] https://ec.europa.eu/growth/sectors/construction/construction-products-regulation-cpr_en
https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32011R0305

[22] https://cordis.europa.eu/project/id/233730/en

Compared with other construction products, for noise barriers as for other relevant Road Equipment (i.e.: safety barriers, vertical signs, etc.), a deeper attention must be paid to the **Use Stage** (B1 to B5), covering the entire working life of the noise barrier product.
Taking care for maintenance also means minimizing the **impact on the traffic flow**. In fact, environmental consequences of **traffic disruption** can reach high values for some indicators impacting the overall score of noise barrier sustainability in many situations, and this seems to be one of the most relevant impacts in the case Road Equipment.

The new developed SOPRANOISE tools: both, the in-situ inspection and the quick measurement method can be applied in an extensive way on a large part of the noise barrier asset. If combined with the correct sampling criteria, these tools will help NRAs and road and railways infrastructure managers to collect robust data and have updated information about the functionality of the noise barriers installed alongside their road networks.

This allows infrastructure managers and operators to:

1. Verify tender requirements for noise barriers after installation and legal approval,
2. Monitor the acoustic performance of the noise barriers on a regular basis during the whole working life of the product,
3. Plan maintenance activities in a more effective and efficient way (based on objective data and results),
4. Ideally prolong the product working life (considering a best-case scenario) and, if not possible, the regular monitoring will help to,
5. Better address the product choice in the tendering process and acquisition of new information to be used for new installation or for upgrading existing ones.

The following table show in more detail how the SOPRANOISE methods can be applied at the different stages, following the scheme of the standard EN 15804:2012+A2:2019 [20] .

Construction Stages according to standard EN 15804:2019	**How the SOPRANOISE methods can be used in the frame of a sustainability assessment**
CONSTRUCTION STAGE: A5: Construction – Installation process	After installation of newly built noise barrier, the whole SOPRANOISE approach can be applied: from the in-situ inspection (step 1) up to the application of the full EN methods (step 3). The SOPRANOISE approach can be used to verify tender requirements and legal approval.
USE STAGE: B1: Use B2: Maintenance B3: Repair B4: Replacement B5: Refurbishment	The SOPRANOISE approach can be used to monitor the acoustic performance of the noise barriers on a regular basis during the whole working life of the product. It becomes a useful tool to plan maintenance activities in a more effective and efficient way (based on objective data and results). A regular monitoring will also help to better address the product choice in the tendering process and acquisition of new information to be used for new installation or upgrading existing ones. Decisions about repairment, replacement or refurbishment of the noise barrier can be improved with the SOPRANOISE approach: in particular step 1 and step 2 can be used to identify which noise barrier fields have to be replaced or not.
END-OF-LIFE STAGE: C1: Deconstruction demolition	Before taking any decision on the final decommissioning of a noise barrier, the SOPRANOISE approach: in particular step 1 and step 2 can be used in order to identify which noise barrier fields have to be discarded or not.

Moreover, relevant synergies can also be found between the SOPRANOISE outcomes (and their possible applications) and the activities of a new research project, called PROCEEDR[23], in the frame of the CEDR call 2020 on Resource Efficiency and the Circular Economy: this new project aims to create two tools to enable National Road Administrations to identify innovative and sustainable solutions to facilitate the transition from linear to a circular economy in the field of roadside infrastructure.

3 At Noise Barrier Installation

NB Installation

Noise Barrier **Approval**
(product & installation)

After the Noise Barrier Planning, the Noise Barrier Design and the Noise Barrier Procurement, if the specifications are correctly drafted in their call for tender, relevant authorities should have received offers that they can objectively understand and compare to conclude for the right choice.

It is here strongly advised to clearly and officially specify the calculation method for comparing the offers within the procurement documents.

Having received the test reports attesting the conformity of the submitted *products* (important reminder: only products *certified* against the relevant characteristics should be considered), authorities may check if the *products* that *will be* delivered and installed are correctly *manufactured.* Sometimes within some sensitive manufacturing processes, it could happen that the quality varies and the performances deviate from the ones certified.

Tests at the installation are, however, more appropriate to check the conformity: not only the conformity of the *products* themselves, but also the quality of their *installation* as this installation may affect the final acoustic performances of the noise barrier.

In fact, the *product manufacturer* very often differs from the *contractor* who installs its *products*. The *certified performances* delivered by the *product* tests reports do correspond to specific *installation* procedures. The installer must strictly follow those procedures for the final noise barrier to stay *conform*; installation procedures should be delivered to NRAs.

Considering the *acoustic* characteristics, the SOPRANOISE 3-step innovative approach now brings new perspectives to proceed with the noise barriers approval at installation.

Its principles are shown in the flowchart in Figure 33.

Thanks to the SOPRANOISE 3-step approach [19] , authorities can check the conformity of the installed noise barrier following an interesting progressive method that will place the right investment at its right place and keep the full EN 1793-5 [5] and EN 1793-6 [6] tests for relevant conformity conclusions:

- Step 1. **In-situ inspection** to detect any visible default before any test (to be done on the whole barrier length),
- Step 2. **SOPRA quick tests** with the possibility to investigate/sample the whole length of the noise barrier in a relevant manner (to be done in the maximum safe and cost effective conditions),
- Step 3. **Full EN 1793-5 [5] and EN 1793-6 [6] tests** for concluding about conformity of the noise barrier (to be limited to where Step 1 and Step 2 give relevant facts).

[23] https://proceedr.project.cedr.eu/

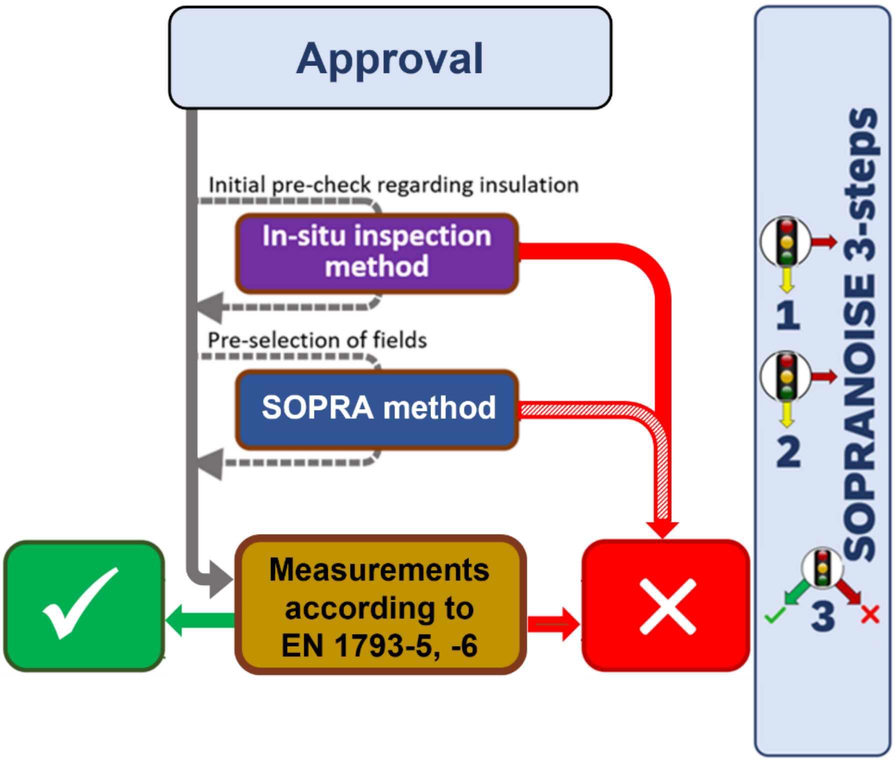


Figure 33: SOPRANOISE 3 successive steps to official approval of installed noise barriers [19]

- If authorities are willing to **officially approve the intrinsic acoustic performances** of the installed noise barrier, the only methods certifying the measured values are those ones described in the standard "full" methods EN 1793-5 [5] (for *sound absorption/reflection*) and EN 1793-6 [6] (for *airborne sound insulation*), i.e. **Step 3**.
- However, **Step 1: In-situ inspections *can be very useful* before carrying out any other ones**: those inspections can detect if defects are already existing that could degrade the IL performance: such defects must be directly rejected before carrying out any further tests[24].
- **Step 2: Quick SOPRA method *can be very useful* before applying the standard "full" methods**: as this method is much quicker, safer and less expensive that the standard "full" methods, it is the best method for having a relevant overview on the whole length of NB. Moreover, it yields the possibility to establish relevant statistics and a relevant sampling procedure of *where to limit* the tests with the standard "full" methods.

  Additionally, authorities could also fix criteria of rejection at this level[25].

[24] warning: no approval can be given at this stage.
[25] warning: no approval can be given at this stage.

4 During Noise Barrier Lifetime

NB Effective Use / Lifetime
Noise Barrier **Monitoring**
Noise Barrier **Lifetime Tests**
Noise Barrier **Maintenance**

During the operational phase of a noise barrier, care must be taken to maintain its noise effectiveness (the fundamental *intended use* of a noise barrier) as long as possible to consequently protect the environment as it has to.

4.1 Noise Barrier Monitoring

Regular monitoring of works ensures their durability: such monitoring is routine for infrastructure administrations. *In-situ inspections* (SOPRANOISE Step 1) can be considered as simple and easy inspections that can be done during the usual road/railway infrastructures monitoring. So, at a very small additional cost to the existing monitoring procedures, Step 1 adds now the acoustic dimension. Those visual inspections will, of course, allow some evaluation of the possible degradations on the IL (Insertion Loss) performance of the barrier. However, while limited to the effect of *visible defects* on the intrinsic airborne sound performance and the resulting extrinsic IL performance, inspections can also be useful, to some extent, to obtain indications about the durability of sound absorbing materials. When in specific doubt, one can of course carry out some tests with the SOPRA method (SOPRANOISE *Step 2)*, but this is not the usual aim of monitoring operations.

4.2 Noise Barrier Lifetime tests

Lifetime tests could be considered for two reasons:

- The procurement of new noise barriers specified clearly that the acoustic performances of the noise barrier had to be checked periodically against some values required in the specifications (verification of the acoustic performances conformity along the noise barrier lifetime);
- But also, to collect information on existing noise barrier about the evolution of their lifetime, what could help in statistics about the durability of some kind of noise barriers and/or their materials.

4.2.1 Control of Acoustic Conformity along the Noise Barrier Lifetime

In such cases, the Noise Barrier Approval scheme described in “At Noise Barrier Installation” applies and only tests carried out with the standard ”full” methods EN 1793-5 [5] (for *sound absorption/reflection*) and EN 1793-6 [6] (for *airborne sound insulation*), i.e. *Step 3,* can conclude about conformity.

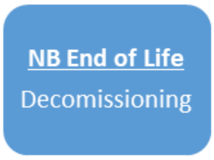
4.2.2 Collecting Information about Acoustic Durability of Products

In this case, depending the intention of the authority willing to collect this information, *Step 3* is facultative.

4.3 Noise Barrier Maintenance

Finally, the SOPRANOISE 3-step approach can also be very useful to better understand the necessity of maintenance operations, choosing the right step for the right target conclusion.

5 At Noise Barrier End of Life



Decommissioning is a very important stage in a noise barrier life cycle: authorities must understand the costs this will represent at the end of the life cycle.

The total cost of ownership should always be evaluated/considered when ordering the construction of a new noise barrier project: NRAs should estimate and consider fully the lifetime costs associated with ENB procurement and installation, maintenance and end-of-life disposal.

5.1 End of life of single components

Generally, the end of life of road equipment depends on: the material deterioration (declared working life), accidents randomly occurred and/or modification of the site conditions along the road/railway.

End of life of a noise barrier may happen at different times as working life of structural elements is often longer than acoustic elements.

SOPRANOISE in situ inspection tool and quick measurement method can be used to determine the lack of (acoustic) functionality of the product installed.

In case no maintenance activities can be foreseen, this corresponds to end of life of the product and implies the replacement of acoustic elements or of the noise barrier as a whole.

5.2 Recycling and reuse of materials

Decommissioning phase implies dismantling activities and the possibility either of recycling materials or reuse of components that may be used in the new installation.

In case of reuse of components after refurbishment activities (i.e., change of absorbing material inside cassette panels) or the adaptation of acoustic elements (panels) to the existing structural elements (posts). Disposal of material should be done in accordance with the Waste Framework Directive (WFD) [24] .

SOPRANOISE measurement methods can be used to assess the correct assembling of the noise barrier.

6 Conclusions

Noise barriers can provide very high and effective noise reduction but only if they are correctly designed, built, monitored and maintained during their whole lifetime.

Taking advantage of the outcomes of the SOPRANOISE research, the present guidelines provide relevant information at every stage of a new noise barrier project: before its installation (planning, design, procurement), at the installation (approval), during its whole use/lifetime (monitoring, lifetime tests, maintenance), up to the decision about its end of life.

It is highly recommended that the NRAs consider noise projects in a holistic way in order to keep their value as long as possible: the SOPRANOISE 3-step approach provides now appropriate methods for assessing the acoustic performances, whenever and wherever.

7 References

[1] EN 14388:2015, *Road traffic noise reducing devices - Specifications,* 2015.

[2] EN 1793-1:2017, *Road traffic noise reducing devices - Test method for determining the acoustic performance - Part 1: Intrinsic characteristics of sound absorption under diffuse sound field conditions,* 2017.

[3] EN 1793-2:2018, *Road traffic noise reducing devices - Test method for determining the acoustic performance - Part 2: Intrinsic characteristics of airborne sound insulation under diffuse sound field conditions,* 2018.

[4] EN 1793-3:1997, Road traffic noise reducing devices - Test method for determining the acoustic performance - Part 3: Normalized traffic noise spectrum.

[5] EN 1793-5:2016+AC:2018, *Road traffic noise reducing devices - Test method for determining the acoustic performance - Part 5: Intrinsic characteristics - In situ values of sound reflection under direct sound field conditions,* 2018.

[6] EN 1793-6:2018, *Road traffic noise reducing devices - Test method for determining the acoustic performance - Part 6: In situ values of airborne sound insulation under direct sound field conditions,* 2018.

[7] EN 16272-3-1:2012, Railway applications - Track - Noise barriers and related devices acting on airborne sound propagation - Test method for determining the acoustic performance - Part 3-1: Normalized railway noise spectrum and single number ratings for diffuse field applications.

[8] EN 16272-3-2:2014, Railway applications - Track - Noise barriers and related devices acting on airborne sound propagation - Test method for determining the acoustic performance - Part 3-2: Normalized railway noise spectrum and single number ratings for direct field applications.

[9] CEDR Technical Report 2017-02, State of the art in managing road traffic noise: noise barriers, Brussels, Belgium (2017).

[10] P. Reiter, A. Fuchs, et. al., *SOPRANOISE Deliverable D2.1, "Review of the physical significance of EN 1793-1, EN 1793-2, EN 1793-5 and EN 1793-6"*; 2020.

[11] M. Conter, et. al., *SOPRANOISE Deliverable D2.2, "Final report on the main results of WP2 (including M2.1, M2.2. and M2.3) – Acoustic assessment of the intrinsic performances of noise barriers"*; 2021.

[12] M. Chudalla, F. Strigari and W. Bartolomaeus, *SOPRANOISE Deliverable D3.1, "Final report on the main results of WP3 (including M3.1, M3.2 and M3.3) – In-situ inspection tools"*; 2021.

[13] M. Garai and P. Guidorzi, *SOPRANOISE Deliverable D4.1, "Report on the development of the new quick methods in laboratory"*; 2021

[14] M. Garai and P. Guidorzi, *SOPRANOISE Deliverable D4.2, "Report on the validation of the new quick methods in-situ with recommendations for proper use"*; 2022

[15] J-P. Clairbois, P. Houtave, N. Lebasi, C. Nicodème and M. Garai, *SOPRANOISE Deliverable D5.1,* "*WP5 Intermediate progress report including M5.1, M5.2 and M5.3"*; 2021

[16] J-P. Clairbois, P. Houtave, "How multiple reflections can cause a degradation of performance of noise barriers," Proc. Internoise '96, 763–768 (1996)

[17] D.C. Hothersall and S.A. Tomlinson, "Effects of high-sided vehicles on the performance of noise barriers" The Journal of the Acoustical Society of America 102, 998 (1997);

[18] D. C. Hothersall, K.V. Horoshenkov, P.A Morgan, M.J. Swift, "Scale modelling of railway noise barriers" Journal of Sound and Vibration, Volume 234, Issue 2, 6 July 2000, Pages 207-223

[19] J-P. Clairbois, M. Conter, M. Chudalla, F. Strigari, W. Bartolomaeus, M. Garai, N. Lebasi and C. Nicodème, *SOPRANOISE Deliverable D5.2, "SOPRANOISE Final report - Guidelines for NB use and scientific report"*, 2022

[20] EN 15804:2012+A2:2019 - Sustainability of construction works - Environmental product declarations - Core rules for the product category of construction products

[21] EC.EUROPA.EU, LIST OF BODIES NOTIFIED UNDER DIRECTIVE : Regulation (EU) No 305/2011 - Construction products : https://ec.europa.eu/growth/tools-databases/nando/index.cfm?fuseaction=directive.pdf&refe_cd=Regulation%20%28EU%29%20305%2F2011&requesttimeout=900

[22] prEN 17383, Road traffic noise reducing devices - Sustainability: Key Performance Indicators (KPIs) Declaration (at ENQ stage)

[23] S. Eggers, C. Popp, S.V. Legarth, T.H. Pedersen, C.P. Volk, H. Bendtsen, T. Gjestland, *FAMOS (FActors MOderating people's Subjective reactions to noise), "Guidebook on how to reduce noise annoyance"*

[24] Waste Framework Directive (WFD), Directive 2008/98/EC of the European Parliament and of the Council of 19 November 2008 on waste and repealing certain Directives, consolidated text 2018: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A02008L0098-20180705

[25] Danish Vejdirektoratet, Rapport 429 – 2013 "*Effektiv planlægning af skærme mod trafikstøj"*, Vejdirektoratet, 2013