Conférence Européenne des Directeurs des Routes

Conference of European Directors of Roads

CEDR TRANSNATIONAL ROAD RESEARCH PROGRAMME 2018

SOPRANOISE

D3.1 – Final report on the main results of WP3 (including M3.1, M3.2 and M3.3) – In-situ inspection tools

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Introduction and structure of deliverable report D3.1

The present document summarises all findings achieved in the frame of work package 3 (WP 3) of the SOPRANOISE project. This work package was started in December 2019, completed in May 2021 and was structured in the following tasks:

- T3.1 – Review of existing in-situ inspection tools;
- T3.2 – Development and testing of methods based on in-situ inspection;
- T3.3 – Description of the in-situ inspection tools and reporting.

The general objective of WP 3 was to demonstrate up to what extent in-situ inspections can yield fair indications on the acoustic performances of installed noise barriers and to establish an inspection method for the qualitative assessment of the possible effect of degradations in noise barriers. Therefore, in-situ inspection tools – mainly based on visual inspection procedures – were reviewed, tested and developed further.

In a first step, a review of existing inspection tools and procedures has been conducted. The starting point was a questionnaire, which was circulated among the CEDR member states (covering European Road Authorities and Research Institutes), to gather information about existing inspection routines and knowledge/experiences on different aspects of the acoustic performance of noise barriers. The results have been summarised in the task report T3.1, delivered in August 2020, which also represents the achievements of milestone M3.1 (*Review of existing in-situ inspection tools*) as a final output of task T3.1. This task report has been included in this document and constitutes the first part of the present deliverable D3.1.

The main goal of task T3.2 was to create an acoustic in-situ inspection procedure that allows a first acoustic assessment of noise barriers, by considering the effects of degradations on the insertion loss. The inspection is supposed to be mainly based on visual inspections and the characterisation of detected defects the barrier. After defining the demands on the inspection method, the development process started. Originating from the theoretical model described in the SOPRANOISE deliverable D2.2, an approximative calculation method was implemented. In a subsequent testing phase, the resulting acoustic inspection protocol has proven to yield a clear and realistic approximation of the degradation effect due to leaks in a noise barrier. The output of the work carried out within this task is summarised in the second part of the present deliverable D3.1, showing the achievement of milestone M3.2 (*Development and testing of methods based on in-situ inspection*).

Finally, within task T3.3, several feedbacks on the developed inspection procedure led to further improvements of the in-situ inspection. Moreover, the scope for the application of the in-situ inspection procedure was defined and the relevant user-oriented documents, including all information necessary to carry out and understand the inspection procedure, were drafted. The corresponding results of this work are assembled in the task report T3.3, which represents the achievement of milestone M3.3 (*Description of the in-situ inspection tools and reporting*) – the third and last part of the present document D3.1.

With this, the acoustic in-situ inspection procedure is fully formulated and the first step in the progressive 3-step approach pursued in the SOPRANOISE project is established.

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SOPRANOISE

T3.1 report – Review of existing in-situ inspection tools

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1 Introduction

Work package 3 (WP 3) of SOPRANOISE deals with the methods for *in-situ* inspection of noise barriers. The present report on task 3.1 (T3.1) represents the review of existing inspection tools. Further steps will be to develop and test an enhanced procedure for *in-situ* inspections, that allows a first assessment of the performance of noise barriers (T3.2). The conclusion of these two tasks will lead to the description of a new and more reliable *in-situ* inspection tool.

As all other buildings of the traffic infrastructure, e.g. tunnels or bridges, noise barriers are usually included in inspection routines to ensure safe transportation, the attention of existing routines being mainly on stability and obvious damages.

Up to now, the priority in the maintenance procedures is mainly on safety and durability, but not directly on the NB acoustic performances. But the demand for tools for the assessment of the acoustic performance of NB increases.

On one hand residents expect the promised noise levels while, on the other hand, the national road authorities (NRAs) want to know whether they get what they ordered when a new NB is built: additional procedures are thus needed to complement the existing inspection routines and include acoustic aspects to assess their performances.

In this report, a **visual and aural *in-situ* inspection tool** is defined as a relevant procedure to inspect NB, including their acoustic performances (sound absorption and airborne sound insulation), **without carrying out any measurement but only by visual and aural examinations**. The result of this procedure will be a protocol and a quick assessment of what can be the acoustic performance.

This procedure will be ideally implemented in visual inspection procedures already existing in some countries. However, this procedure has not to be confused with the ***in-situ* quick method,** where **(quick) acoustic measurements** take place. This is covered by WP 4.

2 The SOPRANOISE questionnaire

SOPRANOISE targets to improve the existing in-situ assessment of NB for the 2 following situations:

1. The assessment of newly built NB to check if their guaranteed performances are achieved.
2. The monitoring of existing NB to check their acoustic performance throughout their whole lifetime, thereby protecting residents from disturbing and annoying noise.

To review the existing assessment procedures, a questionnaire has been circulated: this questionnaire sent to the European road authorities and research institutes was about the existing knowledge and experiences on different aspects of the acoustic performance of existing NB barriers. Answers have been received from Austria, Belgium (Wallonia and Flanders), Cyprus, Estonia, Iceland, Ireland, Norway, Poland, Sweden and Switzerland: a summary of the answers relevant to WP 3 (i.e.: questions “a” to “d”) is listed below.

2.1 Question a: Theoretical models of the impact of defects

Are there, to your knowledge, theoretical models for noise barriers describing the impact of defects on sound insulation and absorption or any other investigations, which allow conclusions about the intrinsic properties of noise barriers based on the description of defects?

Some participants mentioned the CEDR “Technical report 2017-02 State of the art in managing road traffic noise: noise barriers” [1]: this report is discussed in Section 3.

None of the participants knows about any existing theoretical model describing the impact of defects on airborne sound insulation and sound absorption.

Austria mentioned an “acceptance procedure” for NB along roads regarding the sound reflection [2]. However, it is not based solely on visual inspections of defects, but to a large extent on sample measurements (see Section 3).

In Germany, the theoretical description of defects in NB with respect to their impact on sound insulation and absorption was subject of a research project (published in 2019 [3]). To get an idea about the “real” effect of defects to the environment, a radius of influence is defined, depending on certain properties of the defect. For more information on this, see T 2.3 of WP 2.

The “acceptance procedure” developed in Austria follows another approach and helps to assess the acoustic performance of both newly built NB and older NB which are monitored during their lifetime. This procedure can partly support WP 3, but is mostly to be seen in the “Quick methods” of WP 4. The Austrian procedure is described in chapter 3.

2.2 Question b: Databases of acoustic performances

Do you have or do you know about acoustic investigations/measurements specifically on damaged/aged noise barriers or databases, in which information about the performance (loss) of damaged/aged noise barriers can be extracted?

The majority of the countries answered that they do not have any knowledge of investigations or measurements on damaged or old NB.

Some participants of the questionnaire referred to the above-mentioned CEDR report [1]: this report is discussed in Section 3.

Belgium (Flanders) mentioned reports of measurements for insulation and reflection at new and old NB, including information about their age and NB type: these reports have been included on the specific SOPRANOISE cloud.

In Ireland, there were also different investigations (ongoing from 2017) on used NB [4], some of them also combined with visual inspections. The inspections have been carried out on site, whenever possible, or by a drive-by survey with a visual recording device: some of them are still in progress, the corresponding reports are also included on the specific SOPRANOISE cloud.

In a Swedish survey from 2007 [5], noise abatement measures were evaluated regarding their calculated and measured effectiveness (see Section 3).

Austria refers to a method, designed by the "Austrian National Road Administration" (ASFINAG) [2], for checking a specific noise barrier section as a whole. More precisely, certain sections are visually inspected and the assessment at different locations is classified into 3 classes (good, not clear and bad). Then measurements are carried out at some selected locations. Eventually, a mathematical approach allows the assessment of the overall effectiveness of the observed noise barrier section.

Switzerland has answered this question with "no", however, a research report from 2009 [6] was found, in which the insulation and absorption of five aged NB (three made of aluminium cassettes, one of concrete and one of wood) and one aged absorptive covering were investigated (see Section 3.9).

2.3 Question c: Existing visual / aural inspection procedures

What are known procedures/best-practices for a first visual/aural inspection of old noise barriers? Are there practical experiences using these procedures?

Summarised, most countries do have frequently visual inspections for NB about safety issues and to monitor the state of the construction for non-acoustic aspects. The following list gives an overview of differences regarding the inspections:

- Cyprus does not have an inspection procedure.
- Poland does not have any inspection tool because NB are being used only since a short period of time.
- Iceland added that they are normally reacting after residential complaints.
- The Estonian guide for inspections [7] gives an overview of the different noise barriers along national roads, and sets requirements for the inspection procedures. Condition levels (1-4, from very good to very poor) are provided for different types of noise barriers.
- Belgium (Wallonia) has developed a "Management control system" [8] (see Section 3.3) which gathers various parameters of detected NB defects. Acoustic parameters or consequences are missing.
- Belgium (Flanders) does quick visual inspections (driving along) every 2 years to replace or to improve the worst five NB.
- Ireland categorises their NB after visual inspections into a 3-step (traffic light) system, where "green" represents good condition, "yellow" reasonable condition and "red" poor condition.
- Sweden is currently developing a new procedure for inspections, which may include parameters affecting the acoustic performance, like status of absorbent materials and surface treatment of vegetation.
- Switzerland classifies NB into a 5-level system after inspection. If the status of a NB is one of the two worst levels, measurements or calculations have to be carried out.
- Austria is following their test manual as mentioned in Section 2.1; a more detailed description follows in Section 3.

It can be clearly seen, that the need to set up a standardised procedure for visual and aural inspections at NB is growing in the mind of the national road administrations.

Some countries have already started with procedures of different levels of complexity, as e.g. in Belgium/Wallonia or Germany. They have good new ideas that can help to set up an acoustic assessment based on visual and aural inspection.

2.4 Question d: Assessment procedure for acoustic performance

Do you know about any assessment procedure for the acoustic performance of damaged/aged noise barriers based on the results of a visual/aural inspection?

There are no other visual or aural assessment procedures mentioned from the participants.

3 Existing inspection tools on installed NB

The first appearance of NB dates back about 50 years ago: initially, focus was mainly concentrated on the NB construction to guarantee their stability, the traffic safety and the health of the users. The loss of the acoustic performance over time was, and is up to now, just a subordinated subject. Within the last few years however, the subject of a potential loss of acoustic performance due to failures under construction, damages from mechanical impact, or defects by degradation of any kind, became more prominent and new investigations on this subject arise.

3.1 CEDR Report

3.1.1 General

The CEDR technical report 2017-02 [1] the current state of the art that has to be known regarding noise barriers: It gives an overview of the working principles and the different factors that can influence their effectiveness.

It introduces the acoustic and non-acoustic standards to establish the performance of NB and to obtain a CE marking (product standard EN14388). The standards concerning the acoustic (series EN 1793), the non-acoustic (series EN 1794) and the long-time performance (series EN 14389) are briefly explained.

The report also lists different types of NB concerning their material, their shape and their aesthetic appearance. The diversity of construction heights and prices is shown, and a reference list of design handbooks of different European Member States is given.

3.1.2 *Defects*

Leaks that can occur – by mistake already when building up a NB – due to mechanical impacts or from degradation over time and results of first investigations of their effect on the acoustic and structural performance are discussed. The impact on the intrinsic values in terms of reduction of the airborne sound insulation or sound absorption is significantly and clearly measurable. The shape and size of leaks can also have an influence, not only to the measured single number rating, but also to the frequency spectra. A logical effect of leaks on the extrinsic performance (insertion loss, IL) of a NB is, that they are clearly noticed in short distance to the leak and lose influence with increasing distance. This is, of course, dependent on two factors:

1. the distance of the leak to the diffraction edge: the nearer the leak is situated to the diffraction edge, the lower is its influence; this becomes clear when considering that a “leak” at the top end of a NB just decreases its height a few centimetres.
2. the initial performance level of the NB: the effect of a leak in a NB with a high airborne sound insulation is greater than in a NB with a low airborne sound insulation; this becomes clear for the trivial case that a leak in a non-existing NB does not have any influence.

Last but not least, the visual condition or the aesthetic view of a NB is not to be underestimated. Investigations show, that even if a NB is rusty or has a visual damage without effect on the acoustic performance, residents feel less comfortable and assume that the noise level is increased.

3.1.3 *Inspections and monitoring*

When carrying out an inspection certain important points of a NB are of particular interest depending on the current stage of the NB lifetime: although a basic NB seems to be a simple construction (*"just a wall"*) from a structural point of view, from the acoustic perspective, it is a complex and sensitive object. These important points are listed in the report for new barrier installations as well as for monitoring all along the NB lifetime. The two lists are consistent in most points and address the key areas on which the attention must be turned to when doing visual and aural inspections. However, beside the common types of NB, complex constructions of different and maybe new materials or compositions do also exist for that reason, the listing cannot be seen as being exhaustive and complete yet. The list represented in Table 1 can still be regarded as a good basis for localising damages and setting up a first structured scheme when inspecting NB for acoustic reasons. Some of the defects that occur not only affect sound absorption or airborne sound insulation, but also create new noise sources. For example, under the influence of wind, loose fastening parts might rattle or missing seals might cause the NB elements to move back and forth within the post. These additional noise sources are referred to in the last column of Table 1.

Table 1: List of the key areas for visual and aural inspections

Impact of	Component	Impact on		Additional noise source
		Airborne sound insulation	Sound absorption	
Physical degradation, defects or damages	Acoustic elements	X	X	
Quality, condition and placement	Seals	X		
Stability and alignment	Posts	X		
Quality and condition	Fastenings to secure acoustic elements	X	X	X
Quality, condition and placement	Gravel boards/ground level seals	X		
Quality, condition, alignment and fitment	Doors, access gates…	X		
Vandalism	Acoustic elements, seals, fastenings, doors, access gates…	X	X	X
Vegetation		X	X	

For newly built NB the recommendation is to consider a construction supervision as early as possible and together with the manufacturer’s installation instructions. With these manufacturer’s installation instructions, weak points, or points where special care in the building process is essential to ensure the acoustic performance of the NB, can be spotted in the blueprints before the real inspection, and thus better detected on site. The big advantage of supervision during the construction phase is that some mistakes can be revealed and faults in later installations can be avoided. This ensures the expected performance of the NB for the residents and saves a lot of time and money for the manufacturer and the NRAs: the compliance with contract requirements is fulfilled and the NB fits its purpose.

If it is not possible to do the supervision when a NB is being built, it should be made as soon as possible after its completion: to achieve the highest quality, the inspection should preferably extend across the whole length of the NB and on both sides. If this is difficult, or considered to be unnecessary, random selected sections of the NB should be inspected at least by driven pass-by. The acceptance of an NB project should not take place before this kind of assessment has been performed. This guarantees the compliance with the contract requirements and, thus, that the intrinsic acoustic performances are in line with the values declared in the CE marking. Even if a newly built NB is correctly inspected, found in good order, and is accepted in line with the contractual requirements, a frequent visual monitoring of NB in use is strongly recommended to ensure the acoustic performance over the rated lifetime. The frequency of inspections also depends on the kind of NB materials and the climate conditions. A wooden NB in a valley cut through a forest does need more attention than a concrete NB on an elevated open field. An example of procedure for frequent and periodic inspections is given in Section 3.2 for Germany.

3.2 Germany

As basis for budget and building decisions, the Federal Ministry of Transportation and Digital Infrastructure (BMVI), together with the Federal Highway Research Institute (BASt), installed a database of road buildings for the road building maintenance management in Germany.

The structure and contents of this database are regulated in the **ASB-ING** [9] ("Anweisung Straßeninformationsbank: Segment Bauwerksdaten", English: "Instructions for the road information system: building data").

The German standard **DIN 1076:1999-11** [10] "Ingenieurbauwerke im Zuge von Straßen und Wegen - Überwachung und Prüfung" (English: "Engineering structures in connection with roads - inspection and test") [5] regulates the scope and implementation of monitoring and testing.

3.2.1 ASB-ING

The ASB-ING constitutes the basis of a formal and consistent procedure and quality of collected data for every road building. It comprises all constructions of buildings along federal roads like tunnels, bridges, road restraint systems, sign gantries, "green" bridges, noise barriers, noise encapsulations. After the construction of a road building, a new entry in the database is created. The database consists of a classification system where every building has its own number (if necessary, also a part-building number), geometrical data, data of orientation, material (numerous possibilities for compositions), acoustic characteristics, age…, and a field for free text entry. The database provides the foundation for testing and monitoring in specified regular cycles. The corresponding reports are also entered in the database and can be viewed at any time.

3.2.2 DIN 1076

The standard DIN 1076:1999-11 states the rules for frequent **testing** and **monitoring** (as defined below) to secure the stability, road safety and durability of all engineering structures alongside roads. 3 documents are to be created for the inspections; these documents are presented at next page:

1. Building directory (German: “Bauwerksverzeichnis”) includes information:

    - building number
    - responsible authority
    - station details
    - nearest place
    - position above/below
    - type of building
    - main dimensions
    - maintenance obligation
    - load capacity

2. Building book (German: “Bauwerksbuch”)

    Includes an overview of the most important data of the building and serves for the registration of all inspections carried out. The scope of data to include results from the above-mentioned ASB-ING, where all necessary data for every road building is listed. Measures taken to remedy defects or damages must be entered here.

3. Building file (German: “Bauwerksakte”)

    The building file should contain all the information about the engineering structure that is relevant for maintenance and ongoing processing; it contains (only regarding NB):

    - contents
    - drawings
    - proof of stability
    - corrosion protection plans
    - steel lists
    - part lists
    - investigation results, expertise
    - dimensional results
    - building inspectorate approvals
    - approval in individual cases
    - acceptance certificates
    - list of used building materials
    - construction diary
    - information about construction history and construction process
    - documents about later changes and conversions
    - inventory drawing
    - all inventory documents
    - cost statements of the building
    - essential contracts
    - official approvals and certificates
    - others

Figure 1 illustrates the start screen of the database software for road buildings “SIB-Bauwerke” (“Straßeninformationsbank-Bauwerke”: road information database – building structures): one can retrieve the data of a specific building like in Figure 2, but it is also possible to do statistical evaluations with respect to different characteristics concerning the considered buildings, e.g. the age of NB (Figure 3). Therefore, it is possible to generate a suitable output, for example for all NB made of aluminium cassettes with a height between four and five meters in the federal state of Bavaria. It is also possible to modify the design of the output data table. There is several information to choose from: type and name of the building, year of construction, different data of the location like road identifier, coordinates, orientation, dimensions of the building, responsible authorities, materials, colour but also information about the state and constitution of the building (for an example see Table 2).

Figure 1: Start screen of the software "SIB-Bauwerke"

Figure 2: Overview screen of a NB in the software "SIB-Bauwerke"

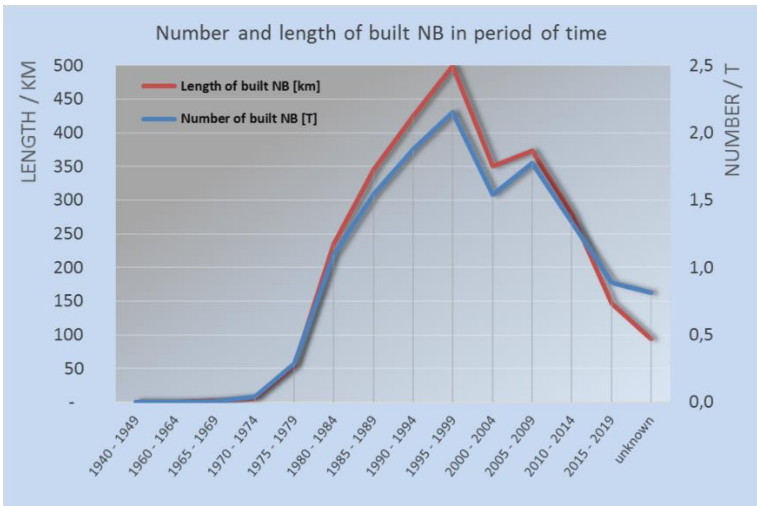


Figure 3: Evaluation of number and length of a specific NB type depending on the age (taken from the software "SIB-Bauwerke")

Table 2: Example of an output table of the software “SIB-Bauwerke”

No.	Name	Location	Length	Material	Departement	Year of construction	No highway	Condition
4408660	LSW / A2 FR Oberhausen km 451,566 -km 453,580/LSW / A2 FR Oberhausen km 452,105 - km 452,665	Gelsenkirchen	578,43	Beton/Stahlbeton	ANL Hamm	2004	A 2	3,5
4407893	A2 FR Oberhausen km 464,1-465,02/A2 FR Oberhausen km 464,79-465,02	Gladbeck	242	Beton/Stahlbeton	ANL Hamm	2001	A 2	3,5
4017520	LSW / A33 FR Bielefeld km 41,46-km 43,4/LSW / A33 FR Bielefeld km 42,484-km 43,029	Schloß Holte Stukenbrok	539,24	Beton/Stahlbeton	ANL Hamm	1993	A 33	3,5
3918656	LSW A2 "Drakesiedlung", FR Oberhausen 315,6-316,3/LSW A2, FR Oberhausen, km 315,654-315,805	Bad Salzuflen	148,38	Beton/Stahlbeton	ANL Hamm	1998	A 2 (Ast)	3,5
4409848	LSW A2 Recklingh. FR Ob km 444,54-444,75/LSW A2 Recklingh. km 444,54-444,75 FR Oberhausen	Recklinghausen	276	Kunststoff	ANL Hamm	1984	A 2	3,4
4408730	LSW A2 Nord FR Ob (Tunnel-Fußweg Parkstadion)/LSW / A2 FR Oberhausen km 455,545-455,812	Gelsenkirchen	269,36	Beton/Stahlbeton	ANL Hamm	2004	A 2	3,4
4408729	LSW / A2 FR Hannover km455,032-456,173/LSW / A2 FR Hannover km 455,852 - km 456,173	Gelsenkirchen	320,65	Beton/Stahlbeton	ANL Hamm	2005	A 2	3,4
4408660	LSW / A2 FR Oberhausen km 451,566 -km 453,580/LSW / A2 FR Oberhausen km 452,71 - km 453,25	Gelsenkirchen	531,21	Beton/Stahlbeton	ANL Hamm	2005	A 2	3,4
4408660	LSW / A2 FR Oberhausen km 451,566 -km 453,580/LSW / A2 FR Oberhausen km 451,56 - km 452,05	Gelsenkirchen	497,35	Beton/Stahlbeton	ANL Hamm	2005	A 2	3,4
4407894	LSW A2 FR Hannover km 464,26-464,74/LSW A2 FR Hannover km 464,26-464,36	Bottrop	108	Beton/Stahlbeton	ANL Hamm	1992	A 2	3,3
3918656	LSW A2 "Drakesiedlung", FR Oberhausen 315,6-316,3/LSW A2, FR Oberhausen, km 315,830-315,860	Bad Salzuflen	32	Beton/Stahlbeton	ANL Hamm	1998	A 2 (Ast)	3,3
4409849	LSW A2 Recklingh. FR Ob km 443,69-444,42/LSW A2 Recklingh. FR Ob km 443,89-444,42	Recklinghausen	545,3	Kunststoff	ANL Hamm	1979	A 2	3,5
4409849	LSW A2 Recklingh. FR Ob km 443,69-444,42/LSW A2 Recklingh. FR Ob km 443,69-443,87	Recklinghausen	180	Kunststoff	ANL Hamm	1979	A 2	3,5
4707716	LSW Gartencenter Turkenburg FR Köln/LSW Gartencenter FR Köln (l = 252 m)	Hubbelrath	252	Holz	ANL Krefeld	1985	A 3	3,4
4505621	LSW Neukirchen-Vluyn (Südseite der BAB)/LSW östl. Sittermannstraße	Neukirchen-Vluyn	224	Leichtmetall	ANL Krefeld	1978	A 40	3,4
4505621	LSW Neukirchen-Vluyn (Südseite der BAB)/LSW westl. Sittermannstraße	Neukirchen-Vluyn	210	Leichtmetall	ANL Krefeld	1978	A 40	3,4
4408827	LSW A2 Gladbeck FR Hannover km 459,89-460,38/LSW A2 Gladbeck FR Hannover km 460,4-460,74	Gladbeck	502	Beton/Stahlbeton	ANL Hamm	1996	A 2	3,4
4408743	LSW FR Hannover Auffahrt PWC-Anl. km 453,7-453,8	Gelsenkirchen	104,3	Beton/Stahlbeton	ANL Hamm	2005	A 2	3,4
4407893	A2 FR Oberhausen km 464,1-465,02/A2 FR Oberhausen km 464,1-464,36	Gladbeck	220	Beton/Stahlbeton	ANL Hamm	2001	A 2	3,4
3918656	LSW A2 "Drakesiedlung", FR Oberhausen 315,6-316,3/LSW A2,FR Oberhausen, km 315,597-315,609	Bad Salzuflen	18	Beton/Stahlbeton	ANL Hamm	1998	A 2 (Ast)	3,4
4408745	LSW /A 2 FR Oberhausen km 453,850 - km 454,120/LSW / A 2 FR Oberhausen km 453,979 - km 454,120	Gelsenkirchen	145,32	Beton/Stahlbeton	ANL Hamm	2005	A 2	3,2
4116711	LSW / A2 FR Oberhausen km 346,550 - km 347,110/LSW A2 FR Oberhausen km 346,76 - km 347,08	Gütersloh	347,58	Beton/Stahlbeton	ANL Hamm	2000	A 2	3,2
3918660	LSW "SCHULWEG Ast A2 km 0,0-0,16/LSW Ast A2 km 0,0-0,0173	Bad Salzuflen - Biemsen-Ah	40,42	Beton/Stahlbeton	ANL Hamm	1999	A 2 (Ast)	3,2
4407904	LSW A2 Bottrop FR Hannover km 466,34-466,99	Bottrop	630	Beton/Stahlbeton	ANL Hamm	1986	A 2 (Ast)	3,5
3918656	LSW A2 "Drakesiedlung", FR Oberhausen 315,6-316,3/LSW A2, FR Oberhausen, km 316,129-316,299	Bad Salzuflen	170	Beton/Stahlbeton	ANL Hamm	1998	A 2	3,5
4408660	LSW / A2 FR Oberhausen km 451,566 -km 453,580/LSW / A2 FR Oberhausen km 453,26 - km 453,33	Gelsenkirchen	197,06	Beton/Stahlbeton	ANL Hamm	2005	A 2	3,3
3918656	LSW A2 "Drakesiedlung", FR Oberhausen 315,6-316,3/LSW A2, FR Oberhausen, km 315,860-316,129	Bad Salzuflen	264	Beton/Stahlbeton	ANL Hamm	1998	A 2 (Ast)	3,4

3.2.2.1 Testing

For the execution of tests, the following information is provided in the standard: regarding the frequency of testing, different types of inspections with varying levels of detail are considered.

3. Main checks

   The first main check has to be carried out before the final acceptance of the construction work. The second main check before the limitation period for the warranty ends. After this the buildings are subject to a main check every six years.

   At main checks every part of the building has to be checked, also the parts not accessible without equipment or facilities. In the test report the defects and damages to be re-checked in future simple checks or additional checks have to be marked. Depending on the material of the specific component, there are different things to look at, like steel corrosion or deformations and cracks at wooden constructions.

4. Simple checks

   Three years after a main check, a simple check has to be carried out normally without need for special equipment or facilities. For a simple check, the outcome of the last main check has to be considered and the defect and damages marked in the corresponding protocol have to be checked. If any critical defects or damages or extensive changes at the building is noticed, the simple check has to be partly or fully extended to a main check.

5. Checks for special occasion

   These checks have to take place after bigger incidences, which influence the status of the building. The scope of the examination results from the special occasion. A check after a special occasion does not supersede a main or simple check.

3.2.2.2 Monitoring

Beside these three kinds of testing, a building monitoring has to take place. A building monitoring consists of inspections and observations. The execution and the outcomes of the monitoring must be logged. If any questionable finding occurs, a “check for special occasion” must be carried out. Competent persons are to be entrusted with the monitoring.

1. <u>Inspection</u>

   All engineering constructions are to be inspected without any big aids for obvious extraordinary changes at the building, extensive defects or damages regularly once a year. An inspection has not to take place in years of main or simple checks. But therefore, they have to be carried out after extraordinary incidents that could influence the stability and road safety (heavy accidents, high water…).

2. <u>Continuous observation</u>

   Within the frame of the general supervision of traffic routes, all engineering constructions are to be observed continuously in the track inspections. Furthermore, two times a year all components have to be observed for obvious defects and damages, though just extensive ones have to be protocolled.

3.2.2.3 Evaluation

The evaluation of the condition of road buildings is specified in detail in two documents [11] [12]. This is to unify the whole system and guarantee comparable scores independently from the inspection staff. Every single defect gets a separate score for the three criteria: "Stability" (S: "Standsicherheit"), "Safety to Traffic" (V: "Verkehrssicherheit") and "Durability" (D: "Dauerhaftigkeit").

The score of the three criteria can have a number from 0 to 4 (see Table 3).
An example looks like: "S=1, V=2, D=0".

Together with the number of occurrences and the propagation of the defect(s) the score becomes multiplied or divided. The overall score of a road building is a function of all single scores of every component of the structure together with several parameters which can vary between the components. The outcome of this evaluation process is a score between 1,0 and 4,0 with one decimal place and is divided into six groups with an assigned period of time to resolve the problem:

1,0 – 1,4	very good condition	
1,5 – 1,9	good condition	long-term action
2,0 – 2,4	satisfying condition	medium-term action
2,5 – 2,9	still sufficient condition	short-term action
3,0 – 3,4	critical condition	immediate action
3,5 – 4,0	insufficient condition	

In the "Guidelines for planning maintenance measures on civil engineering structures" [13], dedicated measures and reset values for every defect of every building component are described in order to revise the condition score after the action taken.

To ensure comparable scores independent from the inspecting person(s), a collection of defects with respective scores ("Gathering experiences based on damage examples") including descriptions and photos is the basis for inspections: this "catalogue of defects" is continuously updated, for example when yet unknown / unlisted defects occur.

The framework described in Section 3.2 is the basis for a high level of road safety and durability of road buildings in Germany.

Table 3: Example of descriptions of scores for “Safety to Traffic” (V)

Score	Description
0	The defect/damage has no influence on traffic safety
1	The defect/damage has hardly any influence on traffic safety; traffic safety is given. Damage repair within the scope of building maintenance.
2	The defect/damage has a minor impact on traffic safety; traffic safety is still ensured. Removal of damage or warning notice required.
3	The defect/damage impairs traffic safety; traffic safety is no longer fully ensured. Removal of damage or warning notice required at short notice.
4	The defect/damage impairs road safety; road safety is no longer guaranteed. Immediate measures are required during the building inspection. Restriction of use must be carried out immediately. The repair or renewal is to be initiated.

3.3 Belgium, Wallonia

The “Walloon Road Noise Division” of Belgium developed a procedure (described in [8]) to monitor the condition of NB. Establishing such a procedure was motivated by the existence of many NB alongside the roads of Wallonia, whose ageing can be questionable. In addition, the developed procedure can also be used for the acceptance of newly built NB.

In a first, step a database of all NB, including all their characteristics and locations, was created. The second step consisted of setting up an inspection procedure with the aim to describe the state of the NB. It allows to derive a “health indicator” to efficiently prioritise the investments for restoring or removing “ill” NB.

The procedure consists of the following three complementary main documents presented at next pages.

<u>Main document n°1: “List of defects”</u>

The first main document is a list of the major defects that were found after the investigation of several NB of different types. The list differentiates six main parts of NB (poles, elements, absorbing material, foundation, environment and other elements). These main groups are numbered from 1 to 6. This number is also the first digit of a three-digit code. The remaining two digits precisely specify the defect type, like rust, impact, degradation, vegetation, moisture, etc. The possible defects are respectively listed within the main groups (see Table 4).
As an example, a deformed panel has to be considered in the second group and gets the code “220”. Moreover, for a better visualisation, particular colour codes represent the respective code number.

Table 4: Main document n°1: “List of defects” of the Walloon management procedure

Wallonie mobilité infrastructures SPW

Inspection des écrans antibruit

Catalogue des défauts - version 2.0

N°	Dénomination	Commentaires	Fig.	N°	Dénomination	Commentaires	Fig.
1	**Poteaux**			4	**Fondation**		
110	Dégradations de la peinture	Epaufrures, cloques, ...		41	*Fondation en béton*		
120	Rouille			411	Fissures		
130	Déformation			412	Rouille		
140	Impact			413	Epaufrure		
150	Fixations dégradées	En pied de colonne		414	Armatures apparentes		
160	Absence ou mvt du joint latéral			415	Mouvement joint caiss/dalle		
170	Dégradation du joint			416	Dégradation du joint		
1900	Autres défauts			4190	Autres défauts		
2	**Caissons, Panneaux**			42	*Couplage avec dispositif de retenue*		
210	Rouille			421			
220	Impact			422	Rouille		
230	Fixations dégradées ou absentes	Identifier des battements		423	Armature(s) apparente(s)		
240	Végétation			424	Epaufrure		
250	Humidité	Taches sombre, moisissure		425	Dégradation de la bavette	y compris les fixations	
260	Absence d'élément	Elément complet ou bardage		426	Absence de la bavette		
270	Encrassement	Y compris les grafitis		4290	Autres défauts		
2900	Autres défauts			5	**Environnement**		
3	**Matériau absorbant**			510	Végétation		
310	Humidité			520	Encrassement		
320	Matériau détérioré	Lambeaux, morceaux, ...		530	Non inspecté		
330	Absence du matériau			5900	Autres défauts		
340	Matériau apparent			6	**Autre élément**		
350	Voile de protection détérioré			610	Défaut à définir		
3900	Autres défauts			620	Pas de défaut		

Main document n°2: “Illustration of the defects”

The second main document is a photographic illustration of every type of defect that has been found (see Figure 4 at next page). This shall ensure a reproducible identification and classification of defects at inspections. This extensive and steady document establishes the same basis for all inspections and allows an assessment that is “as independent as possible” from the inspection staff.

Figure 4: Main document n°2: “Illustration of the defects” of the Walloon management procedure

Main document n°3: "Working Document"

The third main document is an Excel sheet where the indicated defects of the barriers with their position, comments and linked photos are noted from the inspector (see Table 5).

This table is made available on a tablet device during the inspection. This facilitates the work on site and the subsequent processing.

After the inspection of a whole NB section has been carried out, all the collected information contributes to the "Inspection report". This report is also an Excel file, which consists of eight single sheets, these sheets are:

1. Encoding of defects at front side of the NB

Protocol of the inspections regarding the front side of the NB (see Table 5): at this stage, corrections by the inspector can be made to finalise the document and link the corresponding photos of the defects.

Table 5: Example of encoded defects as in the 1st and 2nd sheet of the inspections report

Locations of defects	Codes of defects	Names of defects	Comments	Photos' number
N° Caisson/Panneau	Code défaut	Dénomination	Commentaires	N° Photos
1A	620	Pas de défaut	4m long 60haut 5 elem	
1A	510	Végétation	gene	
1E	320	Matériau détérioré		
1B	320	Matériau détérioré		
1D	320	Matériau détérioré	Matériau absorbant détérioré.	1
1C	320	Matériau détérioré		
2A	210	Rouille		
2B	320	Matériau détérioré		
2A	220	Impact		
2E	240	Végétation	mou et arbre	
2C	210	Rouille		
3E	260	Absence d'élément	Caissons tombé au sol.	3
3D	220	Impact		

2. Encoding of defects at back side of the NB

In the same way than for the front side: protocol of the inspections regarding the back side of the NB (see Table 5). At this stage, corrections by the inspector can be made to finalise the document and link the corresponding photos of the defects.

3. Location: the "ID card" of the NB

The "Location" sheet is the ID-Card of the respective NB (see Figure 5 left). It comprises the ID Number of the NB, starting and ending points, kilometre position, the responsible road division and an areal view of the whole length of the NB and its surrounding.

4. Characteristics of the NB

It gives an overview of the number of panels and columns, the length of the single panels and the barrier as a whole. Additionally, two more close-up photos are included to give a better impression of the barrier (see Figure 5 right).

5. List of defects (copy of Main Document N°1)

The copy of the main document n°1 (see Table 4) to ensure comparable inspection results.

Date : 18-03-2020

Inspecteurs : D. DUMAY

Rapport d'inspection d'écran antibruit

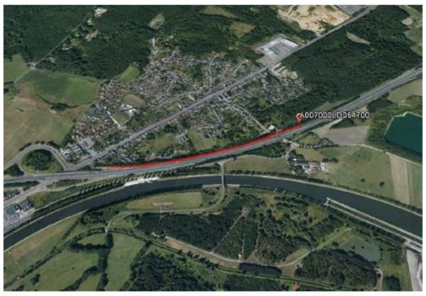
I. Localisation

Numéro ID : A007000LD054700 Comp :

Direction territoriale : 141 Direction des routes de Mons

Localité :

Axe début	BK début	Côté	BK fin	Axe fin
A007000	54700	LD	100	A007203



Wallonie mobilité infrastructures SPW

II. Caractéristiques

Numéro ID	Type	Orientation	Matériau
A007000LD054700	Caisson	H	Aluminium

	Nombre [-]	H [m]	L [m]
Ecran	292	3	1000
Colonne	293	3	3
Caisson/Panneau	5	0.6	5

Vues d'ensemble

Wallonie mobilité infrastructures SPW

Figure 5: Left: "Location"-sheet with all global information to the barrier
Right: "Characteristics"-sheet with detailed information of the barrier

III. Bilan des défauts

☑ Sélectionner tous les défauts

	Dénomination	Avt	Arr
210	Rouille	4	0
220	Impact	3	18
230	Fixations dégradées ou absentes	5	57
240	Végétation	21	185
270	Encrassement	35	26
320	Matériau détérioré	59	0
510	Végétation	36	37
620	Pas de défaut	1	1

	FACE AVANT	FACE ARRIERE
E	33	71
D	23	64
C	28	61
B	26	55
A	29	48

Commentaire général sur l'inspection

L'inspection a mis en évidence une végétation envahissante tant sur la face avant que sur la face arrière. En se développant, elle a endommagé certains caissons comme le montre le rapport-photos.

D'autres problèmes ne vont pas tarder à survenir comme des chutes ou des soulèvements de caissons; les uns provoqués par les arbres qui appuient dessus, les autres par les racines qui passent endessous grossissent.

Le matériaux absorbant est en général dans un mauvais état sur une grande partie du mur, ce qui laisse planer des doutes quant à son efficacité.

Les caissons E à savoir ceux citué sur le haut de l'écran, présentent de façon presque systématique un problème de fixation.

Figure 6: Left: Overview of all identified defects, separated by front and back side of the NB
Right: Number of defects per position and comments

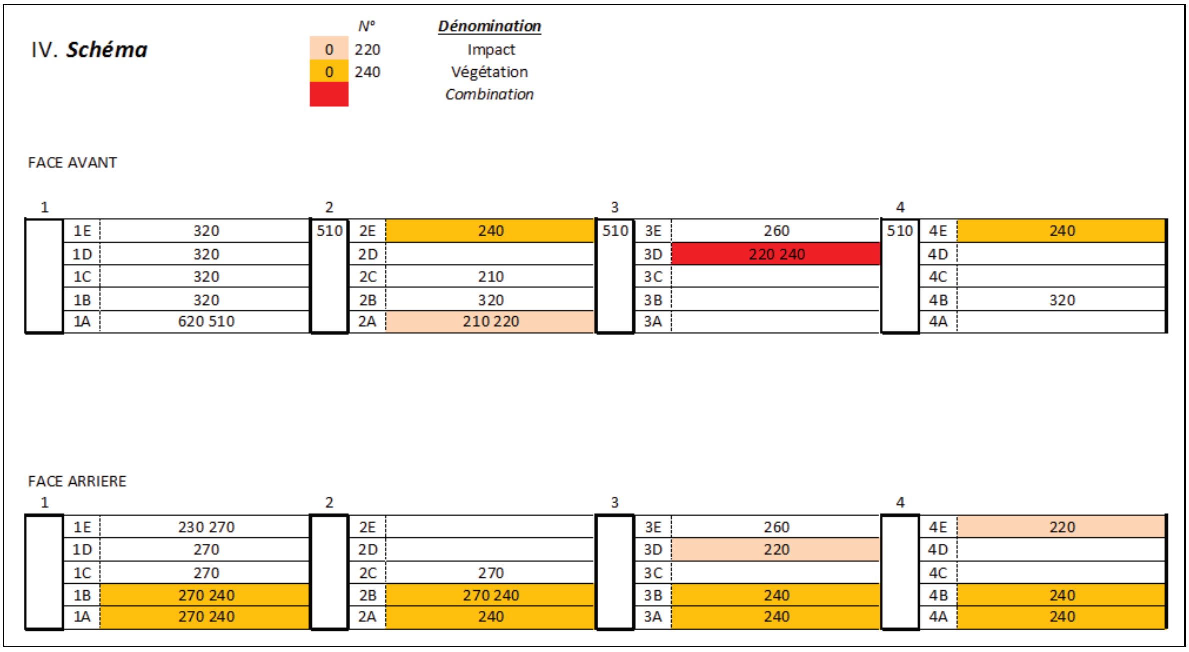
6. Overview

This sheet (see Figure 6) gives (at left side) an overview of all identified defect(s) and their respective number(s), separated by front and back side of the NB. On the right side of the sheet a schematic representation of the NB structure is included as well as the list of the respective comments. The number of damages per element (position) is noted in the schematic representation of the structure.

7. Diagram

On this sheet, the whole NB is displayed with every post and every element field (like the schematic representation of the structure on sheet 6) with the actual number of posts and element fields. The associated defects are assigned to each element including comments and photos. Two fields are available where it is possible to choose specific defect codes. These two chosen defect types will then be illustrated in the scheme with different colours.

If both selected defects are assigned to an element, this will be indicated in red. This sheet is interactive and gives an overall overview of all defects and their location (see Figure 7).


IV. ***Schéma***

	N°	*Dénomination*
0	220	Impact
0	240	Végétation
		Combination

FACE AVANT

1			2			3			4		
	1E	320	510	2E	240	510	3E	260	510	4E	240
	1D	320		2D			3D	220 240		4D	
	1C	320		2C	210		3C			4C	
	1B	320		2B	320		3B			4B	320
	1A	620 510		2A	210 220		3A			4A	

FACE ARRIERE

1			2			3			4		
	1E	230 270		2E			3E	260		4E	220
	1D	270		2D			3D	220		4D	
	1C	270		2C	270		3C			4C	
	1B	270 240		2B	270 240		3B	240		4B	240
	1A	270 240		2A	240		3A	240		4A	240

Figure 7: Diagram of the whole barrier with the possibility to highlight different defects

8. Photo report

This sheet is reserved for photos showing the most important defects that were found during the inspections (see Figure 8). The same pictures are linked to the sheet "Diagram" (Figure 7).

V. Rapport-Photos

1 Matériau absorbant détérioré.

2 Plantation de cyprès juste devant l'écran.

3 Caisson tombé au sol.

4 Matériau absorbant détérioré.

Figure 8: Photos report for the documentation of the identified defects

Based on the inspection reports of all NB, a general “health indicator” is then derived: the different tools within the inspection reports help the inspector to get an overview of the state of the device.

The following points are carefully analysed:

1. Structural and stability aspects

   Indicator of the condition: insurance that it is good or warning if not.

2. Acoustic aspects

   a) Sound absorbing material: If it is not in perfect condition a warning is indicated.

   b) Airborne sound insulation: Indication if placement of all elements among each other and with post and foundation is good or warning if not.

3. Setting of elements

   If elements have a bad setting in the posts, they can generate additional noise by movement and impingement: this mentions if it occurs.

4. Visual aspects

   a) Rust: First, rust is a visual aspect, but if it can spread widely and become a serious problem.

   b) Gaps: This aspect is acoustic as well as visual and can be an indicator of possible structural problems.

With the four-step indicator A to D, were A is the worst and D the best, the “health condition” of the NB can be attributed and a prioritisation of repairs can be established.

New devices

Following the above-mentioned scheme, the development of an inspection report also helps when a newly built NB has to be provisionally accepted: it delivers an evaluation of the new device and helps the contractor/manufacturer to make corrections or repairs. During the construction phase, the work is monitored by agents to determine and control the details of the installation (see “QUALIROUTES” [14]). With a frequent monitoring for newly built devices, a long and efficient service life can be insured, and investments can be used effectively.

3.4 Belgium, Flanders

The “Agentschap Wegen en Verkeer” (AWV – in English: “Agency for Roads and Traffic”) is the responsible department for roads and traffic of the Flemish part of Belgium. It carries out visual inspections for all infrastructures along the road network every two years. For NB, these inspections are executed by car at a speed of about 70 km/h. This is deemed to be sufficient to get a first impression of their general condition.

Following this procedure, the following damage types can be reported:

- sagging of elements
- lacking of elements
- damaged elements or insulation material
- crumbling of wood fibre concrete pavement
- gap between elements
- oxidation of metal elements
- damage caused by collision

For a closer view, heavily damaged NB can be subject to further inspections on site or by Google Street View. Since 2017, the five most severely damaged NB should be replaced.

3.5 Estonia

The first NB in Estonia were built in 2004, with an increasing number from year to year. The principles for visual inspections and the assessment of their condition and performance are set up with the “Guide to the inspection of NB on state roads” [6], which was composed along with the “Bridges inspection guide” back in 2016, but it has not been implemented yet. However, the implementation is in agenda for the near future, as the life cycle of the first noise barriers in Estonia is about to reach its end in the coming years.

First, a register of NB on state roads has been compiled to summarise all necessary technical information. The register is the basis for inspections and subsequent analyses.

The NB register contains all data about the location of the respective NB and all describing data of the building, like geometrical and material information, year of construction and renovation and year of last inspection, including a condition index from 0 to 100 %. Furthermore, data of noise level measurements according to “NT ACOU 056” [7], photos, blueprints and protocols of inspections are also entered in a database during the whole lifecycle. Every NB has its plan of inspection, where the specific time of the planned measurements are specified.

Inspections are usually planed in a four-year cycle, from May until September, depending on weather conditions. The starting point of an actual inspection is the data of the last inspection. Defects of every single element unit (including acoustic elements, foundation, posts…) are assessed with respect to their type and extent, and a condition grade (see below) on a four-point scale is assigned. For every material (steel, brickwork, wood aluminium…) there are definitions to identify the condition. Photos of defects are also taken.

Condition 1: The element is free of defects and signs of use. The overall picture is clean and new. Minor defects such as cracks due to shrinking and discolouration may occur.
Activity: continuation of routine maintenance, cleaning.

Condition 2: The element has minor surface damage, erosion and signs of damaging processes. The overall picture is good but not new and there are clear signs of use. There may be defects and minor geometrical deviations that are not essential for operation.
Activities: continuation of normal maintenance, elimination of local damage with minor repairs and, if necessary, finding out the cause of the defect.

Condition 3: There are damages to the element that do not directly reduce the load capacity and function, but it is advisable to repair or replace these. The overall picture shows damages for which minor repairs are not sufficient. Deteriorating environmental processes have begun to damage the element. There are significant defects and geometric deviations.
Activities: planning of major repairs and exploring the causes.

Condition 4: The element is damaged in a way that the strength and load capacity of the entire structure is affected. The overall view shows that the element is depreciated and needs immediate overhaul or replacement. The element does not fulfil its function and poses a serious risk to the strength of the structure, other elements or safety.
Activity: replace element.

For every NB section and every single element, the number of specific defects in the specific NB section is noted in a table of the database.

In order to assess the condition of a NB objectively, it is necessary to perform an assessment of the airborne sound insulation in parallel with a visual inspection. The document states, that the results of measurements carried out in accordance with the standards EVS-EN 1793-6 and EVS-EN 1793-2 lead to comparable results. It is also possible to use the Nordic method. When using the Nordic method, it is necessary to determine at least one fixed point behind the NB where measurements are performed. These results are to be compared with calculation results (e.g. a strategic noise map model).

The Nordic method can be used if a deterioration in performance compared to the CE certificate is indicated in accordance with the standards EN 14389-1 and EN 14389-2.

The acoustic measurements, together with the categorisation, can be compared with previous measurements and used to predict the state of the NB.

The goal of further analyses is to study the changing condition based on different indicators (type, material, length, year of construction, etc.) in more detail and to forecast changes in the condition of the different groups and necessary repairs.

The purpose of grouping is to create the possibility of "extrapolation" to facilities that were not reviewed in the current year. In the long run, this approach targets at creating models that allow a better maintenance planning for the whole network. In addition, such grouping makes it possible to decide whether a given solution is appropriate.

The Status Index (SI) is the current condition level divided by the maximum possible condition level, assessed on the basis of the inspection routine. Therefore, two indicators are compared:

- current: the current condition of each element
- total: the maximum condition of each element

The condition levels “Condition 1” to “Condition 4” have the following coefficients:

- Condition 1: $S1_{coefficient} = 1$
- Condition 2: $S2_{coefficient} = 0{,}66$

- Condition 3: $S3_{coefficient} = 0{,}33$
- Condition 4: $S4_{coefficient} = 0$

The formula to calculate the actual condition of an element is

$$current = (S1_{amount} * S1_{coefficient} + S2_{amount} * S2_{coefficient} + S3_{amount} * S3_{coefficient} + S4_{amount} * S4_{coefficient}) * weighting\ factor \quad (1)$$

Amount: the number of elements of the respective condition level.

And the formula to calculate the total (best) condition of an element is

$$total = amount * weighting\ factor \quad (2)$$

Here the "amount" represents the total number of all elements[1].

The Status Index *SI* allows to compare all facilities to one another.

$$SI = \frac{\sum current}{\sum total} * 100\% \quad (3)$$

The system is also designed, assuming the assigned unit prices, to calculate costs for repairs. Depending on the condition of the various elements, the appropriate activity for the facility is selected and the total costs for the repairs is calculated. The calculations obtained during the analysis are compared with the work done. In addition to the visual inspection analysis, the measurement results are considered in this section as well and are compared to the designed service life (according to the standard EVS-EN 14389-1).

In the third part of the analysis, the whole network is regarded by considering the results of visual inspections and airborne sound insulation measurements, in order to predict changes in condition and the need for investment.

3.6 Austria

The Austrian Institute of Technology (AIT) together with TAS SV-GmbH developed an "acoustic acceptance procedure" for NB for the Austrian ASFINAG (Austrian National Road Administration). This procedure was mainly developed in order to approve newly built NB but also for having the possibility to perform a so called *in-situ* monitoring of existing NB. It describes approaches for both airborne sound insulation and sound reflection. Parts of the procedure are measurements regarding the standards ÖNORM EN 1793-5 and ÖNORM EN 1793-6 for direct sound field measurements.

The goal is to check a whole contract section of a NB, avoiding an evaluation just based on a limited number of tests (at random) locations and to define a fair choice of the specific barrier fields, which has to be tested with the full method (EN 1793-5 and 1793-6). As it is not possible to measure every single field of the whole NB with the standardised method, a simplified measurement method was developed, in order to speed up the whole measurements process: associated with statistical data processing, it allows the assessment of the acoustic performance of a certain contract section of a NB "as a whole". However, this method still underlies restrictions in terms of accessibility of the NB and safety issues regarding the operators doing the measurements.

[1] Note from the authors: The "weighting factor" was not explained in the document or was lost in the Google translation of the Estonian document and must be requested afterwards.

The acceptance procedure is used for:

- the determination of the product-specific *in-situ* acoustic performance of airborne sound insulation and sound reflection for direct sound fields,
- the verification of the stated performance of the NB,
- the comparison of the dimensioning with the real acoustic performance after completion of the NB, and
- the monitoring of the long-term performance respective to the aging effect of NB.

3.6.1 Procedure for “faster" sound reflection measurements

The quick procedure aims to get an overview of the reflection properties of the single NB fields in short time. In the later evaluation, the data of the quick procedure undergoes a statistical analysis. Then, at some specific NB fields selected after the evaluation, full test regarding ÖNORM EN 1793-5 could be carried out. Based on this data, it is possible to *assess* the reflection characteristics of all considered fields of the whole NB.

Selection of the fields to measure

First, all measurable fields have to be identified and consecutively numbered; non-accessible fields are not to be counted when fixing the total number of fields. The residual fields are used as being representative of the whole NB if they represent more than 50 % of the whole NB.

Quick measurement procedure

The basis of the quick measurement procedure is the ÖNORM EN 1793-5 with adaptations:

- only the central microphone position is used and, like in the former ÖNORM CEN/TS 1793-5:2003, it has a fixed connection to the loudspeaker. This simplifies the subtraction of the direct component of the measurement signal,
- an additional spacer that fixes the distance between the microphone and the NB,
- the whole measurement setup can be quickly positioned by one operator.

With those modifications the distances between NB, microphone and loudspeaker are fixed and no additional measurement equipment is necessary to execute measurements with this setting. However, due to the spacers, the sound field of measurements is affected: this is a constant error to all executed measurements and does not interfere with the aim to obtain an *overview of the distribution* of the single NB field absorption characteristics.

<u>Workflow</u>

The length of NB sections can be from very short (about 100 m) up to several kilometres. Even with short NB, the effort in measuring is important: if the wall is several kilometres long, measurements on every NB field cannot be carried out any more with full tests according to EN 1793-5.

For long NB, a statistical approach is a logic choice: the Austrian method uses a logarithmic approach for NB longer than 1 km.

$$l_s = 0{,}75 \cdot l_g \qquad l_g \leq 1 \text{ km}$$
$$l_s = 0{,}75 \cdot \left(1 + \ln(l_g)\right) \qquad l_g > 1 \text{ km} \qquad (1)$$

where l_g is the whole length of the NB and l_s is the minimum length to be measured.

For barriers up to 1 km the length l_s is capped to 75 % of l_g.

If there are accessibility and / or safety issues and there is no possibility to carry out measurements at the calculated length l_s then, at least 95 % of l_s has to be tested.

During the measurements, free field reference measurements have to be carried out in frequent time steps of at most 30 minutes. Following ÖNORM EN 1793-5, the subtraction of the NB field measurement and the free field measurement is to be proceeded and, together with the standardised traffic noise spectrum, the single number rating of each NB field is calculated. These single number ratings of every measured NB field are the basis data for describing the distribution of the reflection index of the whole NB.

Statistical analysis of the measured data

The distribution of the reflection index of the investigated NB can be displayed with an histogram. This chart represents the homogeneity of the NB fields, or rather the distribution of the measured values. The basic idea to rate the whole NB section is to carry out five full measurements according to EN 1793-5 in addition to the realised quick measurements and convert the data of the quick measurements to “full measurement data” via linear regression. The five measurements have to take place at five NB fields of which each field represents one of the five quantiles of the distribution, where the number of quantiles is P = 5, with p = {0, 10; 0, 30; 0, 50; 0, 70; 0, 90}.

Full measurements at selected NB fields for rating

With the full measurements regarding EN 1793-5 at the five selected fields, the whole bandwidth of the performance with respect to the reflection characteristics of the whole length of the NB is covered.

Creation and evaluation of the regression model

The single number ratings for sound reflection obtained with the quick method $DL_{RI,fast}$ of all measurements become transformed into $DL_{RI,predict}$ by a linear conversion (see Figure 9).
The linear regression is calculated from the five regular measurements DL_{RI}, together with the $DL_{RI,fast}$ of the five corresponding NB fields.

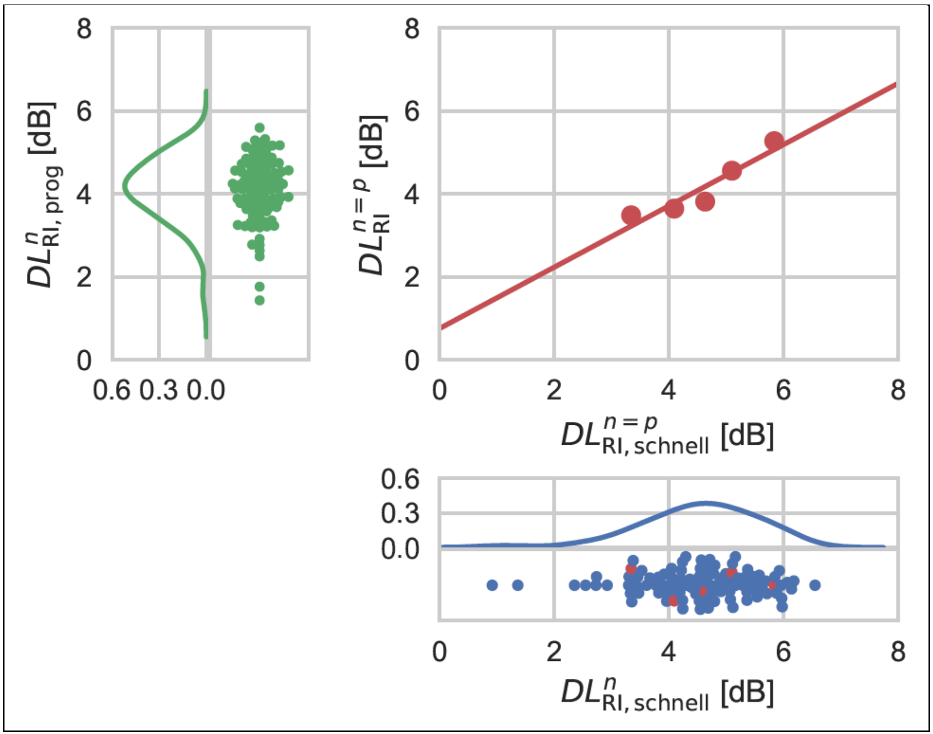


Figure 9: Representation of the conversion of the values measured with the quick measurement procedure into the predicted values using a linear regression model

Overall assessment of the sound reflection properties of the NB section

Based on the generated data as described above, an assessment of the reflection properties of the whole NB section can now be carried out.

It is specified that the values $DL_{RI,predict}$ and DL_{RI} cannot be put on the same level but have to be considered separately: the $DL_{RI,predict}$ obtained by the linear regression model can be used for further statistical evaluations of the predicted acoustic properties for sound reflection.

The values provide information about weak points with respect to sound reflection in the considered NB section and can be used as the basis for further DL_{RI} measurements by the full method (EN 1793-5).

3.6.2 Procedure for assessing the airborne sound insulation properties

The method for determining the airborne sound insulation properties of noise barriers on roads is based on measurements according to ÖNORM EN 1793-6. The aim of the acceptance procedure is to review NB sections as a whole. The minimum value of airborne sound insulation specified in the building tender must be observed at all points of the whole NB section including doors. Due to the high effort, measurements can only be carried out at a limited number of locations. Since weak points in terms of airborne sound insulation such as joints or slots could be easily spotted visually, the procedure described below includes a visual check of a NB section before measurements of the airborne sound insulation at individual points. This is therefore designed in the following two stages:

First stage

The first stage is a visual inspection and documentation of the whole NB section; a classification based on the planning documents of the construction has to be carried out for the inspected NB fields of this section. The classification consists of 3 categories:

Category 1: NB fields without suspected defects (presumably on restrictions regarding insulation properties).

Category 2: NB fields with possible sensitive areas e.g. wide joints and slots, but without evident possibility to look through.

Category 3: NB fields with obvious defects, e.g. joints and slots with clear possibility to look through, obvious installation faults.

It is noted, that slits of already 0,5 cm width lead to a clear reduction of several dB in the intrinsic airborne sound insulation[2].

Each NB field has to be classified into one of the mentioned categories. This has to be documented in the inspection documents (tables, plans, photos).

For the visual inspection, the whole NB section has to be inspected walking on foot. In general, an inspection on the side of the motorway is assumed. In special cases, it also makes sense to view the section from the backside as well, e.g. in cases where construction details relevant for airborne sound insulation are covered by absorber elements on the motorway side).

Second stage

Within the second stage, measurements at selected points of the NB section will be carried out. The measurements according to ÖNORM EN 1793-6 are decisive for the acceptance procedure for airborne sound insulation.

[2] Note from the author: at least for the intrinsic characteristics of airborne sound insulation, but less on the Insertion Loss (IL); see also *Task 2.3: "Influence of acoustic degradation of NB on the total noise reduction"*

Selection of the fields to measure

The selection of the fields and posts to measure results as follows: areas of category 3 can be ruled out because they are considered defective anyway so that a renovation is usually recommended for these *(see also the German ZTV-Lsw 06* [14]*, that NB must not have any continuous cracks, holes, slots or open joints);* the "acceptance procedure" assumes that such areas have a significantly reduced airborne sound insulation.

Then, the number of measurements depends on the length of the NB section:

- Up to 500 m length, measurements at two areas have to be carried out.
- Between 500 m and 1 km length, measurements at three areas have to be carried out.
- For each additional kilometre an additional area is to be measured.

Each "area" consists of measurements at the *element* as well as at *post*. These *element* and *post* positions do not have to be contiguous. The positions for the measurements have to be distributed over the whole NB section with priority to critical areas in the interest of residents.

Locations of category 2 should preferably be selected because reduced insulation values can be expected. For category 1, at least one position should be chosen to document *apparently correct* installations to still check the respect of the tender requirements.

The total number of measurements is not influenced by the division of the NB into categories: if no NB are assigned to category 2, all measurements have to take place at areas of category 1 and vice versa. Provided that at least 85 % of the NB could be assigned to category 1, one measurement within category 2 is enough; in this case, the remaining measurements allotted into category 1.

Regarding the influence of possible sensitive areas of category 2, that are not placed in the vertical centre of the NB field or post, the reference position for the detailed measurements can be shifted vertically: the height of the reference position should be placed near the possible sensitive area, but with a minimum distance of one meter to the top or bottom edge (including plinth).

The Adrienne window length has to be adapted and the valid frequency range has to be respected; to ensure the largest possible valid frequency range, areas with suspected spots in the vertical centre have to be preferred. If this is not possible and the reference positions have to be shifted vertically, the values from the provided product-data are to be used for non-valid frequency bands.

As the NB should meet the requirements on both the *element* and the *post*, the test reports and evaluations are performed separately for the *element* ($DL_{SI,E}$) and the *post* ($DL_{SI,P}$). The energetic averaging of $DL_{SI,E}$ and $DL_{SI,P}$ ($DL_{SI,G}$) is not required, because if both ($DL_{SI,E}$ and $DL_{SI,P}$) meet the required minimum value, then $DL_{SI,G}$ already fulfils the minimum value.

All measured *posts* and *elements* must meet the acceptance criterion: if this should not be the case, the following procedure has to be considered.

Measurement procedure

For airborne sound insulation, as for sound reflection, it is not possible to carry out measurements at every single NB field; actually, it would be even more complex, since both sides of the wall must be accessible, which also makes precise alignment even more difficult.

After all NB fields of a NB section have been classified into the above described categories, airborne sound insulation measurements have to be carried out. The number of measurements results from the length of the NB section and the measurements have to be distributed respectively to category 1 and category 2. Full measurements as described in EN 1793-6 have to be applied.

In the assessment procedure of the sound reflection the execution of the quick measurement at the prescribed number of NB fields represents the main effort, whereas in the assessment of the airborne sound insulation the main task is the inspection and the categorisation. Nevertheless, just a comparatively small number of measurements has to be carried out.

Overall assessment of the airborne sound insulation properties of the NB section

The idea of the accelerated method for airborne sound insulation is based on a statistical derivation whereby it is sufficient to do the specified numbers of measurements respectively to the length of the NB. Taking this as a basis, the determined number of measurements is enough to assess the quality of the whole NB section.

3.7 Sweden

The Department of Maintenance at “Trafikverket” in Sweden performs yearly systematic inspections that focus on safety. Currently, they are developing a new procedure for the inspections of noise barriers that may also include other parameters like status of absorbents, surface treatment, vegetation, etc… Those inspections are planned to be carried out every six years. So far, the inspections are not planned to include acoustic measurements.

To evaluate the effect of defects in NB, Sweden carried out a survey in 2007 [5], where 10 noise abatement measures were evaluated regarding their calculated and measured effectiveness at one to three immission points. One of these measures was a noise reducing road surface. The other measures were NB of different material or combinations. At most of the NB, the calculated and measured insertion loss matched well. At two NB (one glass/PC barrier and one combination of wood and glass/pc), the measured insertion loss was 1 – 2 dB lower than the calculated insertion loss. At one glass/pc NB, the measured insertion loss was 4 dB lower than the calculated one for both considered points. The reason for this difference in the insertion loss was mainly attributed to a too low surface weight of the glass panels.

3.8 Ireland

Ireland carries out inspections. They have a “traffic light” system to categorise the state of the respective NB.

- Green: good condition (i.e. no visible defects)
- Yellow: reasonable condition (i.e. some visible defects e.g. gaps at the bottom of the barrier, absorptive material starting to tear/rip)
- Red: poor condition (i.e. obvious visual defects e.g. holes in barrier, absorptive material removed, barrier swaying as HGVs pass)

There is a standard procedure for undertaking the inspections. Information of how exactly the inspections work will be available before the end of the SOPRANOISE project and included in Deliverable 3.1. After comprehensive inspections in 2018 and 2019, a database has been created in which all relevant data on existing NB, including acoustic properties, were entered. It is to be noted that in Ireland the acoustic characteristics of newly built NB are checked; the wish is to also check those along the lifecycle.

3.9 Switzerland

In 2009 the Swiss research “Unterhalt von Lärmschirmen” (Maintenance of Noise Reducing Devices) [6], commissioned by the Swiss association of road and traffic experts, was published. Herein, defects at NB due to aging and other influences, service life depending on different materials, acoustic state and maintenance were evaluated.

A catalogue of components of different NB was created and typical defects have been documented. Based on these documented defects, inspection sheets to carry out inspections and rate the defects were set up. Hereafter, inspections have to be performed frequently, every five to ten years, using the developed checklists. If deemed necessary, specialists for static or acoustic circumstances have to be involved.

The checklist for NB bases upon the analysis of the detected defects for the four different NB types built in Switzerland and follows the below-listed boundary conditions. The four types are reflective transparent elements, and the three absorbing types made of concrete, aluminium and wood.

Boundary conditions:

- Basis of the checklists are just visual inspections. Special investigations like measurements for the prevention of corrosion or acoustic measurements are carried out just on demand.
- The checklist focuses on defects (one row for each defect).
- The checklist can be used for every kind of NB and (sound absorbing) claddings.
- If one or more serious defects is / are found, more accurate investigations have to be carried out.
- Before the inspections, the inspecting personnel divides the NB in homogeneous sections to assess them each with one checklist, respectively.

In the corresponding research faulty NB were inspected. Some of them were acoustically investigated on site, dismounted, brought into the laboratory and re-installed in the same state as they have been on site, in order to do measurements according to the respective standards. The results were compared with the original acoustic conditions.

<u>Comparison of the on-site and laboratory measurements</u>

The investigated NB had been installed on site for a minimum of 13 years and up to 25 years. Measurements for airborne sound insulation were carried out on site following EN ISO 140-3 (1995), but with real traffic noise. The measurements in the lab were carried out according to EN ISO 140-3 (1995) for insulation and according to EN 20354 for absorption (see Table 6).

In the on-site measurements the noise level was measured on both sides of the barrier (see Figure 10). One microphone was installed on the traffic side to determine the reference noise level, namely 0,5 m underneath the top edge of the barrier and 6 mm in front of a 5 mm thick steel plate with 0,5 m diameter, which was positioned directly on the front plane of the barrier. Behind the barrier, there were nine microphone positions in three horizontal distances to the barrier (1 m, 2 m and 3 m) and three positions in three different heights (0,5 m, 1,5 m and 2,5 m underneath the top edge of the barrier).

In an additional survey, the impact of slits of different width on the airborne sound insulation of NB with aluminium cassettes and NB with wooden elements has been investigated (Table 6). At the aluminium cassettes, which were joined together by a “groove and tongue” connection, a 1 dB decrease of the airborne sound insulation was detected when comparing the correct fitting with a slit of 10 mm. At a flat connection of 2 superimposed wooden elements, the decrease in airborne sound insulation at a slit of the same width was up to 4 dB (see Table 7).

The on-site measurements, together with the laboratory investigations confirmed the assumption of the authors: if the visual state of the NB is satisfactory, the acoustic performance can be assumed as enough. At some of the objects, even an increase of the acoustic performance was stated. Measurements for airborne sound insulation showed that small sporadic slits can acoustically be tolerated in the frame of maintenance. The results of the *in-situ* measurements showed no correlation with the values of the laboratory measurements but are assumed being more meaningful from residents.

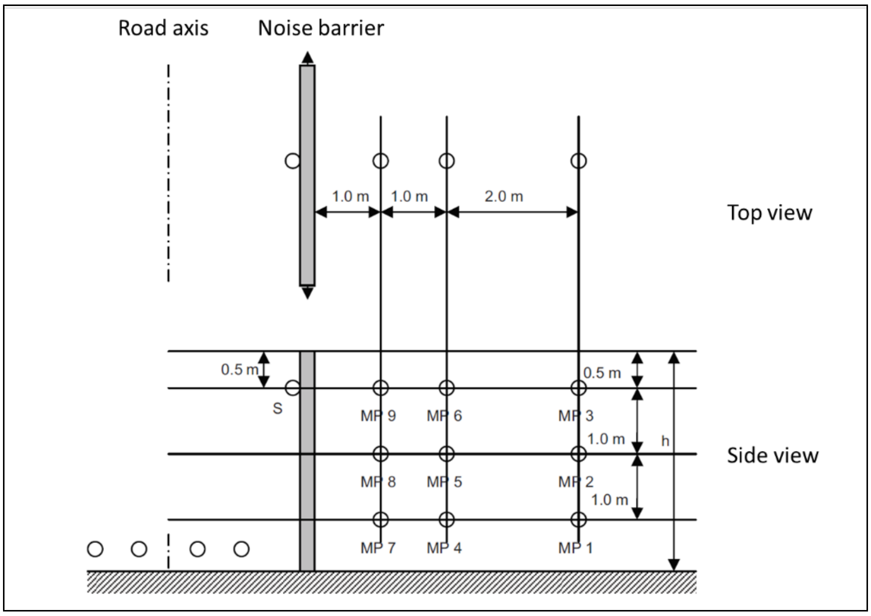


Figure 10: Microphone positions for the on-site measurements at the investigated NB [6]

Table 6: Overview over the investigated NB and their acoustic performance in airborne sound insulation and sound absorption

Noise reducing measure (accuracy +/-1dB)	Aluminium cassette	Aluminium cassette	Aluminium plate and corrugated panel	Absorptive aluminium plate covering	Absorptive concrete	Wooden elements
Years on site (additional storage-time after dis-mounting)	25 (1)	>20 (0,5)	>25 (0,7)	22 (-)	25 (4)	13 (-)
DL_α (dB) new	15	16	20	14	6	12
DL_α (dB) old	20	12	20	13	8	20
Comments (old/new)	identical elements	different height and profile of cassettes	different wavelength of corrugated panel	identical elements	identical elements	identical elements
DL_R (dB) new	26	25	30	-	-	29
DL_R (dB) old	23	25	24	-	-	27

Table 7: Investigation of the impact of slits on the airborne sound insulation of NB with aluminium cassettes and NB with wooden elements

	NB with aluminium cassette groove and tongue			NB with wooden elements stump joint vertical	
Opening of slit in mm	0	5	10	0	10
DLR in dB (accuracy +/-1dB)	23	23	22	27	23

4 Conclusion

The evaluation of the “List of Questions” circulated by the PEB all over Europe and the received information showed that there is a big interest of having an assessment method for a structured maintenance of NB, in order to achieve a long life cycle and guarantee the conservation of the acoustic performance.

A knowledge transfer, as well as an online platform for data exchange was proposed, also to collect experiences related to the effectiveness of noise barriers in relation to the time of exploitation.

Many countries all over Europe are carrying out visual inspections of their NB; these inspections are mostly done in an easy way.

Several countries are setting up more elaborate inspection procedures since a few years to have a better basis for managing the maintenance of their NB. However, these inspections mainly cover stability and safety issues and do not have a specific focus on the acoustical performance… up to now.

Germany has established an inspection procedure including the assessment of the physical condition and a structured procedure considering time management and economic factors. The inspection results help to carry out conservation measures at road buildings since many years.

Wallonia has developed an inspection procedure that has many similarities to the German one. Additionally, they implemented useful tools for the evaluation of inspections. These tools can help to assess the impact of damages on the overall acoustical performance of NB.

Table 8 summarises all the reviewed methods.

Table 8: Summary of inspection methods

Country	Database (incl. acoustics?)	Monitoring	Evaluation of condition	Special attention to current acoustical state
CEDR	N/A	An inspection of newly built NB for acceptance and a frequent monitoring is required.	N/A	Investigations on the effect of defects are mentioned.
Germany	Extensive database of all road buildings, including all building parts of the structure, characteristics (also acoustical), individually definable queries, statistical analysis of overall data with data output. Reports. Photos.	Continuously. Different frequency dependent on complexity of inspection. According to DIN 1076. Catalogue of defects for harmonisation.	Automated evaluation by algorithm after detection of defects (incl. number and extent). Score from 1,0 to 4,0 (one decimal place). Output: Assigned period of time to resolve defect dependent on score.	N/A
Wallonia	Database of existing NB, including acoustic characteristics. Reports. Photos.	Continuously. Different frequency dependent on complexity of inspection. "Illustration of the defects" for harmonisation.	Appraisal into a four-step "Health indicator" (A-D) by inspector after data check. Tools for statistical analysis of defects. Visual overview of occurance of defects.	N/A
Flanders	N/A	Frequently every two years by drive-along inspections (70km/h).	N/A	N/A
Estonia	Database of existing NB, including acoustic characteristics.	Frequently every four years. Definitions to identify condition state (1-4) for different material.	Formula to calculate a condition Index (0-100%) as composition of every single element unit.	Frequent measurements are intended.
Austria	N/A	N/A	By calculations and statistics together with measurements according to EN 1793-5, -6.	Quick method for assessing the acoustical state of a whole NB section.
Sweden	N/A	Frequently every year.	N/A	Investigations on the effect of defects have been carried out.
Ireland	Database of existing NB, including acoustic characteristics.	N/A	Traffic light system for categorisation of state (green, yellow, red).	Recently started and ongoing investigations on used NB.
Switzerland	N/A	Frequently every ~5 years. Documentation of typical defects.	5 (6 with "no record") level to determine the acoustical state of the NB (very good, good, acceptable, bad, very bad).	Yes. Calculations or measurements are carried out if state of NB is bad or very bad. Investigation on the effect of defects have been carried out.

5 Outcomes

The in-situ inspections, consisting of visual and aural examinations, as they are understood in this survey, are meant to be a relevant add-on for existing inspection procedures that are already in operation in the respective countries.

This add-on specifically addresses acoustic requirements.

The documents of (e.g.) Germany or Wallonia - created for their own respective databases and used for the inspections and the monitoring of the long-term performance - can be taken as a good basis and, if necessary, new parameters could be added. These parameters could be specifications like position and dimensions of a detected defect. Wallonia has designed some useful tools, namely the statistical analysis of the number of defects in connection with the vertical position and the type of defect (see Figure 6), as well as an overview sheet that visualises certain defects over a whole NB section (see Figure 7): these tools can be modified to allow acoustic assessments. Here also the results from WP 2 about the effect of defects can be implemented.

The goal of the coming Task 3.2 will be to design and test a new inspection procedure for visual and aural testing of a NB and the subsequent acoustic assessment of the inspection results. On the one hand, this involves the development of an inspection protocol for the acoustic add-ons; on the other hand, the testing of additional tools for the detection of relevant defects. There are two ideas for such additional inspection tools. These are currently being discussed in terms of their applicability and usefulness and are described in the following paragraphs.

Regarding the **visual part of the inspections** it is e.g. conceivable to use a strong light source for a better detection of leaks. This can be used to illuminate one side of the NB while looking for translucent places on the other side. This method is highly dependent on accessibility and the time of day or season.

For the **aural part**, first experiences have shown that a well visible leak could have no hearable effect even when standing directly in front of it if the noise diffracted at the top of the NB delivers the main part to the overall noise level. Here, a possible approach is to develop an ear trumpet based on a horn, which is connected to a headphone via a tube. The headphone does not have any loudspeakers but works practically like a stethoscope which transmits the vibrations to the ear and shields the hearing from the ambient noise.

As a result of the inspections, the assignment of a “traffic light” colour to each NB field is envisaged for the assessed acoustic condition, where green means “good condition”, yellow represents “questionable condition” and red means “acoustically defective”.

For NB that were not accessible the colour black is assigned. For the further procedure, black fields must be made accessible, red fields require repair or replacement, yellow fields are subjected to a further check using the "quick method" (see WP4) and green fields require no further action.

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SOPRANOISE

T3.2 report – Development and testing of methods based on in-situ inspection

February 2021

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1 Introduction

In order to improve the characterisation and systematic control of the *acoustic performance* of a noise barrier, the SOPRANOISE project pursues a progressive approach consisting of three steps: (1) in-situ visual/aural inspections, (2) quick measurement methods and (3) full measurement methods according to EN 1793-5 [1] and -6 [2]. The goal of WP 3 is to elaborate step (1) and develop an in-situ inspection procedure which exploits the possibilities of visual and aural examinations (without carrying out any measurements) to obtain first indications on the possible effect of degradations of the *airborne sound insulation* of existing noise barriers based on simplified calculations. At the state of the art, there is no way to do the same for *sound absorption*. It is relevant to note that the inspection tool described here is not intended to be used for approval of newly built noise barriers, as this can occur only if quantitative measurements are performed. In the first report of WP 3 on Task T3.1 [3], delivered in September 2020 (revised version in November 2020), a review of existing inspection tools and procedures has been presented. Herein, the replies from several European road authorities and research institutes to a questionnaire have also been included.

Based on the results from the review and the theoretical framework presented in the deliverable D2.2 [4] (submitted in January 2021), the present report introduces an in-situ inspection procedure, including an *acoustic* inspection protocol implemented as an *Excel* document, which allows a quick assessment of how the possible effect of degradations of the *airborne sound insulation* of existing noise barriers might be. From this quick assessment, it is possible to evaluate where it is better to apply further testing (i.e. step (2) via the quick method).

After performing the in-situ inspection of a noise barrier and filling out the *acoustic* inspection protocol, the inspector directly obtains an estimation of the consequences of the detected leaks – with respect to the effect of degradations of the *airborne sound insulation* of the noise barrier. As a result, the assignment of a “traffic light” colour to each noise barrier field is considered, where green means “acceptable acoustic condition”, yellow represents “questionable acoustic condition” and red means “acoustically defective”. Depending on the properties and position of the leak, the “critical radius” will be calculated as described in in deliverable D2.2 [4], and a corresponding *acoustic rating* will be given.

For the *acoustic performance* of noise barriers, leaks are of major importance as they can reduce the *airborne sound insulation,* and thus their insertion loss (IL) (see reports on Task 5.2 [5] and Task 2.3 [4]). The present report concerns the *acoustic* part of the detected leaks and focusses on their possible effect on *sound transmission* and on the *insertion loss*. The acoustic consequences of a degradation in the *sound absorption* are, at the state of the art, impossible to generalize and describe theoretically in a simple model. Based on the results of the scenario calculations in Task 2.3 and the considerations presented in Task 5.2, the effect of defects in the absorption material of a noise barrier can only be addressed qualitatively and with a large uncertainty: if degradations of the *sound absorption* performances are suspected, measurements cannot be avoided.

The present report is structured as follows: In Section 2, the approach and idea behind the in-situ inspection method is briefly explained. Both the development process and the connection to the review of Task 3.1 [3] is depicted. Section 3 constitutes a detailed description of the in-situ inspection protocol. The input and output sheets of the *Excel* document, the assumptions made in the estimation of the *acoustic rating for airborne sound insulation* and the calculation of the *critical radius* are explained. The application of the proposed inspection procedure is presented in Section 4. At the example of several noise barriers of different type and condition, the inspection protocol is tested for real-case scenarios and the results are discussed with respect to strengths, weaknesses and significance of the method. In this context, the relation between the *inspection* and the *measurement* via the quick method developed in WP 4 is also discussed. Finally, in Section 5 the results of Task 3.2 are summarized, and a conclusion is given, including an outlook to the remaining steps of this work package.

2 Development of the in-situ inspection method: approach and concept

Before defining the demands on an in-situ inspection method for the evaluation of the *acoustic performance*, the current state shall be briefly recapped by referring to the review of existing inspection methods for noise barriers and the answers to the questionnaire about the existing knowledge on that topic, i.e. the report on Task 3.1 of the SOPRANOISE project [3]:

- Regarding the effect of leaks and recommendations on inspections and monitoring, the CEDR technical report from 2017 [6] has been frequently referred to by the participants of the questionnaire.
- Theoretical models describing the impact of leaks on *airborne sound insulation* and/or *sound absorption* are unknown and not used by the European Road Authorities.
- Only few countries reply to have detailed information about acoustic investigations specifically on damaged or aged noise barriers.
- In most countries, regular inspection procedures for noise barriers (or road infrastructure in general) exist, however, these do not explicitly include acoustic criteria, but normally focus on non-acoustic aspects like stability and safety.
- Furthermore, the replies to the questionnaire illustrated that among the National Road Administrations there are growing interests and more and more efforts to establish a structured in-situ inspection method, which also guarantees the conservation of the acoustic performance throughout the lifetime of a noise barrier.

From this point, a profile of requirements for the in-situ inspection has been framed. Several aspects from the review and other concepts are considered to set up the cornerstones for an acoustic assessment based on visual inspections on site:

1. All in all, most countries already have an inspection scheme to secure the stability, road safety and durability of engineering structures alongside roads; acoustic aspects 'just' have to be included. Thus, in-situ inspections of the acoustic performance have to be conceptualized in a way that they can be **implemented into existing inspection procedures**, which are already in operation in the respective countries. Since the inspection regulations (with respect to frequency, categorisation, reporting etc.) differ from country to country, it is not the aim of this research to override existing national strategies, but rather to provide an *add-on* which specifically addresses acoustic requirements.
2. The basic recommendations and information published in the **CEDR technical report** from 2017 [6] are of course still valid and **of high value** for inspectors of noise barriers; e.g. the description of the effect of leaks on the insertion loss of a noise barrier and the recommendations for a construction supervision of newly built barriers. The list of key areas for visual and aural inspections (summarized by Table 1 in the report of Task T3.1 [3]) serves as a good basis for localising damages relevant for the assessment of the *acoustic performance* of a noise barrier.
3. The visual and aural inspection is supposed to yield a **first approximate estimation** about the possible degradation of the acoustic performance of a noise barrier **without carrying out actual acoustic measurements**. Similar to the first stage of the Austrian procedure (cf. [3]), it is meant to represent the first step (out of three) for giving a first evaluation of possible degradations of the airborne sound insulation and clarify which noise barrier sections have to be investigated further on in more detail by measurements.

4. The required **effort** for the inspection should be **minimal** and **no additional tools** should be required. All relevant aspects for the acoustic assessment should be filled out directly on site. However, pass-by inspections with the help of movie recordings are not considered to be conclusive enough, since relevant information might be missed.
5. The **categorisation of defect types** has been well structured and condensed in the list of defects from Belgium, Wallonia (cf. [3]). This list serves as a comprehensive basis for the *acoustic* inspection protocol presented in Section 3.
6. A common feature in the inspection procedures across several countries (e.g. Germany, Wallonia, Estonia, Ireland, Austria, …) is the **categorisation of the noise barrier condition** into different levels with different action plans, depending on the degree of damage or degradation. This concept is transferred to the in-situ inspection procedure proposed here: the acoustic rating follows a **traffic light system** (inspired by the Irish concept). Depending on whether the acoustic condition is rated as acceptable (green)/questionable (yellow) or defective (red), non-priority actions/further testing via measurements or immediate repairs are advised, respectively.
7. Naturally, even the roughest acoustic rating has to stand on a physical basis. The **theoretical background** for the assessment of the acoustic degradation due to leaks in a noise barrier is provided by the outcome of Task 2.3, i.e. deliverable **D2.2** [4]. The model allows to calculate the (acoustic) radius of influence for different leak characteristics and can be regarded as a first step to relate changes in the *intrinsic characteristic of airborne sound insulation* of noise barriers to changes of the *overall acoustic performance (IL)*. Of course, no definitive decision can be taken on the basis of in-situ inspections only.

These seven considerations formed the starting point for the development of the in-situ inspection procedure. Many more details were the result of iterative tests as well as suggestions coming from the SOPRANOISE consortium and PEB members.

Apart from that, the FAMOS consortium has been contacted, in order to discuss how psychoacoustic effects might be included into the inspection procedure. However, at this point in time, the FAMOS project cannot deliver a final answer to the question how much the visual appearance of a noise barrier influences the noise annoyance. This investigation is still in progress and only preliminary results are available. If the progress allows it, an inclusion within Task T3.3 will be reconsidered.

The next Section explains the structure and working principle of the resulting *acoustic* inspection protocol.

3 Description of the in-situ acoustic inspection protocol

The core of this in-situ inspection is the *acoustic* inspection protocol. It is implemented as an *Excel* document, consisting of five *worksheets*. When performing a noise barrier inspection on site, the inspector can use this *Excel* document to obtain a first assessment of the acoustic condition of the noise barrier.

This can happen either interactively during the general inspection routine by using a portable device (e.g. a tablet computer) or, if such a device is not available, the relevant tables can be printed out and filled in at a later time. The *acoustic* inspection protocol is designed to be easy to understand and handle and requires minimal inputs from the inspector. After filling in all detected leaks and damages, it immediately returns the result of a first acoustic evaluation and the information where further actions (namely, acoustic measurements with the quick method in step (2) of the progressive approach) could be necessary.

3.1 Structure of the in-situ acoustic inspection protocol

The *acoustic* inspection protocol is set up as *Excel* file consisting of five different sheets. The first three sheets 'Location', 'Construction' and 'Defects' are the input sheets and have to be filled in with the information collected during the inspection. The fourth sheet '*Acoustic* assessment' is for output only and directly gives an *acoustic rating* based on the inspector's inputs, including the critical radius up to which the leaks have a non-negligible effect. The fifth sheet 'Settings' allows to change some global parameters, if this is considered to be necessary by the inspector. However, by default this sheet is protected from being changed. An additional sixth sheet 'Calculation' is available in the background but hidden from the user. It contains the internal calculations and also does not require any inputs. In the following Sections, all worksheets of the *acoustic* inspection protocol and their functionality are explained in detail.

3.2 Sheet 'Location'

The general information about the location of the noise barrier is entered on this sheet, mainly as free text. Except for the information about the *emergency lane*, all inputs here are for identification purposes only. The input fields are the following:

road name	Name of the road on which the noise barrier is located.
near	Name of closest neighbouring city.
emergency lane	Input options: "yes" or "no". Important for the assessment of the effect of the leak. It changes the assumed distance between the emission source and the noise barrier, thus, the lengths of the propagation paths of the transmitted and diffracted sound. **Note:** The input of the actual distance to the first lane is not requested, because on the one hand it adds another 'measurement' to be performed during the in-situ inspection. On the other hand, allowing the input of an exact number here creates the 'illusion' of a high accuracy which is not given within the approximations of the calculations. Thus, it is only distinguished whether the noise barrier is close to the first lane (no emergency lane) or separated by an emergency lane. The default values for the two cases are predefined in the 'Settings' sheet (see Section 3.6) and can be modified, if necessary.
from/to km	Inspected road km from the beginning to the end of the noise barrier.
direction	Direction of travel of the inspected noise barrier.
from/to coordinates	GPS coordinates of the beginning and the end of the inspected noise barrier section.

3.3 Sheet ‘Construction’

All Information on the materials used in the design of the noise barrier are protocolled in this sheet. The calculation itself is independent from the inputs made in this sheet. However, records on the noise barrier construction might be helpful for further investigations or cause studies. The input fields are the following:

main construction material Main component of the entire construction. Input options: all common noise barrier materials.

combined with Two further (optional) input possibilities for materials, which the noise barrier is combined with.

absorbing front/back? Input options: “yes” or “no”. For each material used, it can be specified whether the front and/or the back side is sound absorbing or not.

Note: As stated in the introduction (Section 1), no assessment of the effect on *sound absorption* is taking place within the framework of the in-situ inspection.

material of posts If desired, the material of the noise barrier posts can be chosen here. Input options: “steel” or “concrete”.

3.4 Sheet ‘Defects’

This is the central input sheet of the in-situ *acoustic* inspection protocol. All information on the detected defects are filled in on this sheet. The table allows to record up to 50 different defects. Except for the first and last column (*field no.* and *additional notes*), all inputs have to be selected from a dropdown list or via check boxes. This makes the actual inspection process faster and easier to handle on site. The entry fields in the ‘Defects’ sheet are:

field no. Number of the noise barrier field with the located defect; must be an integer number. This can be either an official infrastructure identification number or a running number, counting all noise barrier fields of the inspected road section.

Note: The *field no.* does not have to be entered in ascending or descending order. However, it is important that the numbering of the noise barrier fields is consistent and correct relative to one another, since the distance of neighbouring defects is calculated based on this number. In other words, noise barrier fields without defect also have to be considered when counting. For more details see Section 3.7.3.

NB side Side of the noise barrier on which the defect is detected; for localisation purposes only. The selection “front” refers to the unshielded (road) side and “back” means the shielded side behind the barrier.

field height Height of the noise barrier field with the located defect. Input options: values between 2 and 12 m in steps of 0.5 m. For values in between set to the closest available value.

defect location Describes on which noise barrier component the defect is located; for localisation purposes only.

type/cause of defect Different defect types and causes describing the appearance of the leak. Multiple selections are possible (e.g. this can be applicable, if deformations occur due to vegetation). The categories used here are based on the “List of defects” of the Walloon management procedure (cf. Section 3.3. in [3]) but condensed to the acoustically relevant entries.

	Note: The selections made for the type or cause of the defect are not considered within the acoustic assessment itself. However, the information might be helpful and important for dealing with the damage after inspection, and therefore should be protocolled.
view through	Defines the degree of transmission for the calculation. If "yes" is selected, a transmission coefficient of $\tau = 1$ will be assumed; if "no" is selected, $\tau = 0.5$ will be assumed.
position /m, vertical	Vertical position of the defect within the noise barrier field, i.e. height of the defect above ground. Input options: ranges between 0 and 10 m in steps of 0.5 m. If uncertain between two ranges, set to the lower one.
position /m, horizontal	Horizontal position of the defect within the noise barrier field. Input options: “left”, “middle” and “right.” This information is protocolled for localisation purposes only and not used for the actual acoustic assessment (cf. also Sections 3.7.2 and 3.7.3).
size /cm, vertical	Average expansion of the defect in vertical direction. Different size ranges are selectable. If uncertain between two ranges, set to the lower one.
size /cm, horizontal	Average expansion of the damage in horizontal direction. Different size ranges are selectable. If uncertain between two ranges, set to the lower one.
additional notes	Additional field for entering comments as free text. Any further aspects – not covered by the *acoustic* inspection protocol – might be helpful for subsequent analyses and decisions. These can concern e.g. the visual and aural impression of the inspector on site (i.e. the subjective perception whether the detected leak has an effect on the acoustic performance of the noise barrier or not), the general noise barrier condition and/or its surroundings, or qualitative comments on the absorption material.

In addition to filling in the ‘Defects’ sheet, it is highly recommended to take photographs of the leaks and damages, as done in the approach of the Walloon management procedure (illustration of defects, cf. Section 3.3. in [3]). This ensures a reproducible identification and allows corrections in the post-inspection analyses. Cross-references to the corresponding photographs can then also be included in the field *additional notes*.

3.5 Sheet ‘Acoustic assessment’

This sheet presents the result 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. It should be remarked that the word “assessment” used in this context does not mean a definitive judgement of the acoustic quality of the noise barrier, being based on simplified assumptions and not on measurements.

Two different types of *acoustic* assessment are included: on the left, the result of the calculation is given 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 <u>overall</u> *acoustic* assessment, the superposition of leaks close to each other has to be considered. An approximation for such an overall assessment is given on the right of the ‘Acoustic assessment’ sheet. The details on how the superposition is calculated are given in Section 3.7.3.

The output fields in the 'Acoustic assessment' sheet are:

field no. Number of the noise barrier field with the located defect; taken from the sheet 'Defects' and sorted in ascending order.

acoustic condition Traffic light rating of the *acoustic condition* based on the inspection inputs made on the first three *Excel* sheets. The meaning of the colours is included as a legend in the sheet.

Green: *acceptable acoustic condition*, non-priority actions required for airborne sound insulation. No conclusion possible for sound absorption.

Yellow: *questionable acoustic condition*, further testing could be required for assessing the effective airborne sound insulation (e.g. passing on to quick measurement method).

Red: *defective acoustic condition* regarding airborne sound insulation, repairing required.

critical radius /m Calculated 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. The higher the critical radius, the bigger is the acoustically affected area due to the leak. The value in the left table follows directly and only from the properties of the corresponding leak. The value in the right table is a superposition of neighbouring leaks, i.e. an estimated overall assessment at the position of the corresponding noise barrier field. See Section 3.7.3 for the full details.

The detailed background of the calculations and approximations made to obtain these results is described in Section 3.7.

3.6 Sheet 'Settings'

In the last *Excel* sheet 'Settings', the inspector has the possibility to change a few global parameters. In general, modifications are not necessary here, since the default values serve as a good approximation within the accuracy of the method. In most cases, more accurate values will not alter the results of the *acoustic* assessment considerably. For this reason and in order to avoid an incorrect use, this sheet is locked by default and a warning message is included.

Nevertheless, in exceptional cases it can be useful to change some of the global settings. To do so, the protection of the *Excel* sheet can be removed. The customisable parameters are:

size of NB field /m Size (width) of the inspected noise barrier field; the default value is 4 m. The field size is used to determine the (approximate) distance between defects when calculating their superposition. A weighted addition of the critical radius is carried out – with the weighting factor depending on the distance between the defects. See Section 3.7.3.

If the widths of the inspected noise barrier fields are significantly smaller or larger, this value can be adjusted here to obtain a more realistic estimation of the superposition effect.

thresholds for critical radius for colour rating Thresholds specifying the trigger values of the critical radius for the acoustic traffic light rating. By default, the noise barrier field is assessed to have a *defective acoustic condition* (**red**), if the critical radius of a defect exceeds 50 m. A *questionable acoustic* condition (**yellow**) is indicated for values between 15 and 50 m.

Important: The default values are based on observations and tests carried out within the present research and represent a good compromise. Of course, it can be advisable – under certain circumstances – to choose thresholds which are appropriate for the situation on site: If no residential/sensitive buildings are close by, it might be acceptable to select higher thresholds. On the other hand, if residents are living in close proximity to the noise barrier, stricter values might be required.

distance to first lane with and without emergency lane /m	Distance from the noise barrier to the first traffic lane (emission source), corresponding to d_{NB} in Figure 1 of Section 3.7.1 below, for the case with and without emergency lane in between. In the calculations, this value defines the lengths of the propagation paths of the transmitted and diffracted sound.

Generally, changes are not required here (cf. note in Section 3.2), but if the inspected noise barrier is very close to or very far away from the first traffic lane (i.e. the distance significantly different from the default setting), the value can be adjusted. However, the consequences for the *acoustic* assessment are supposed to be minor.

3.7 *Acoustic Calculation*

The in-situ *acoustic* inspection protocol contains another sheet named 'Calculation'. This sheet is hidden (and protected from modifications) and exclusively working in the background. It lists all data and intermediate steps on which the calculations are based. No inputs can be performed by the inspector. However, for the sake of full transparency, it displays the internal calculation and the global boundary conditions as well as the results relative to each noise barrier field.

In the following Sections, the calculation of the critical radius and the acoustic assessment are explained in detail, including the underlying geometry, the assumptions made for approximation and the estimation of the superposition effect in cases of more than one leak.

3.7.1 Underlying geometry

The underlying geometry for the calculation of the critical radius in the presence of a leak in a noise barrier is shown in Figure 1 as a side view. For better practicability, some simplifications are made.

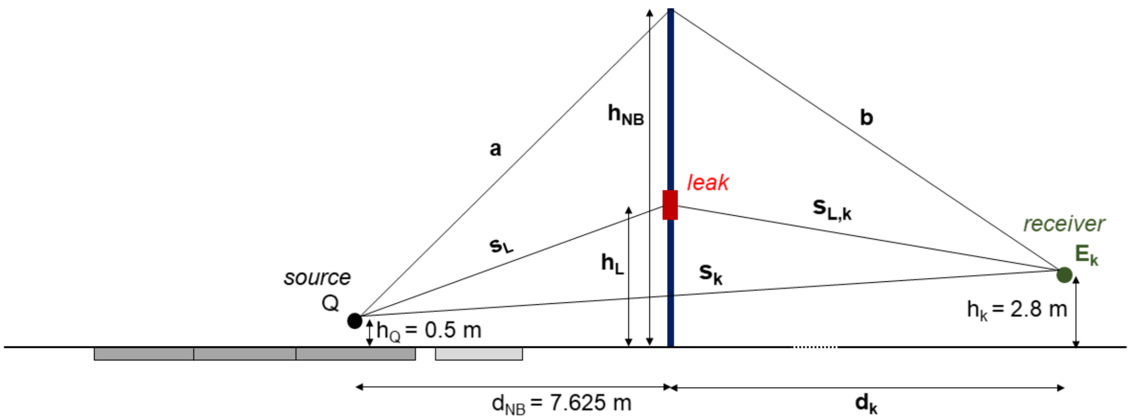

Figure 1: Underlying geometry for the calculation of the critical radius in the presence of a leak

Since the result of the *acoustic* inspection is not supposed to be exact, but a first approximation to decide where further testing is needed for airborne sound insulation, this is considered to serve as a good approximation. A reproduction of the exact geometry on site is not expedient and will not yield notable improvements of the *acoustic* assessment. The assumptions are:

- Only the closest lane to the noise barrier is considered as *emission sound source* and this *sound source* is assumed to be at 0.5 m above the ground.
- The noise barrier is situated at a distance of 7.625 m from the centre of this lane. In cases without emergency lane this distance reduces to 5.125 m (cf. also the explanations given in Section 3.2 and 3.6).
- A two-dimensional description is chosen, i.e. source, leak and receiver are assumed to be situated in line perpendicular to each other.
- The receiver is assumed to be at 2.8 m above the ground.[1]

The meaning of the measures and parameters in Figure 1 are as follows:

d_{NB}	perpendicular distance from source to noise barrier
d_k	perpendicular distance from noise barrier to receiver
s_k	direct distance from source to receiver
s_L	direct distance from source to leak
$s_{L,k}$	direct distance from leak to receiver
a	direct distance from source to top noise barrier edge
b	direct distance from top noise barrier edge to receiver
h_Q	height of source above ground
h_L	height of leak above ground
h_{NB}	height of considered noise barrier field
h_k	height of receiver above ground

It is important to keep in mind that this simplified geometry is chosen such that an easy and fast first estimation of the *acoustic condition* can be derived. Within the accuracy of the approximation, an exact model of the geometry or even a full three-dimensional approach has no greater benefit.

The goal of the assessment is to distinguish between a *defective acoustic condition* (**red** condition) and an *acceptable acoustic condition* (**green** condition) and to identify leaks which require a more accurate *acoustic analysis* (**yellow** condition) via the quick measurement method developed in WP4 of the SOPRANOISE project and/or the full method according to EN 1793-6 [2].

When degradations of the sound absorption performance are suspected, sound absorption measurements must be carried out with the quick method and/or the full method according to EN 1793-5 [1], because the in-situ inspection tool cannot draw quantitative conclusions about it.

[1] The value of 2.8 m is a typical immission height assumed for the ground floor, taken from the German Guidelines RLS-90. This choice should also be considered as an approximation. Allowing an exact input here, presumably does not improve the assessment results significantly.

3.7.2 Acoustic rating and critical radius

The calculation of the critical radius in the presence of a leak in a noise barrier and the corresponding *acoustic (traffic light) rating* are based on the theoretical model described in the SOPRANOISE deliverable D2.2 [4] (in particular Section 2.2 in the respective report). For better clarity, the following paragraph is cited from there:

In the presence of a leak, an acoustical critical area behind the noise barrier is formed, in which the influence of the leak is dominant over the diffraction and the sound insulation of the barrier reduces significantly. At more distant immission points beyond this area the effect from the leak is negligible and the reduction of the sound insulation is not critical any more. We define the critical area by the criterion

$$L_{m,t} \leq L_{m,b} - 10\ dB \tag{1}$$

or by the criticality condition

$$\xi = L_{m,t} - L_{m,b} + 10\ dB. \tag{2}$$

In these equations, $L_{m,b}$ describes the total immission at receiver point E_k due to the diffraction across the top edge of the barrier and $L_{m,t}$ the total immission due to the transmission through the leak […]. For $\xi > 0\ dB$ the corresponding receiver point lies within the acoustical critical area, where the diminished sound insulation due to the leak is relevant. For $\xi < 0\ dB$ the presence of the leak has no significant influence on the sound immission. In other words, the condition $\xi = 0$ defines the border (or radius) of the critical area with dominant impact of the leak. See Figure 2.

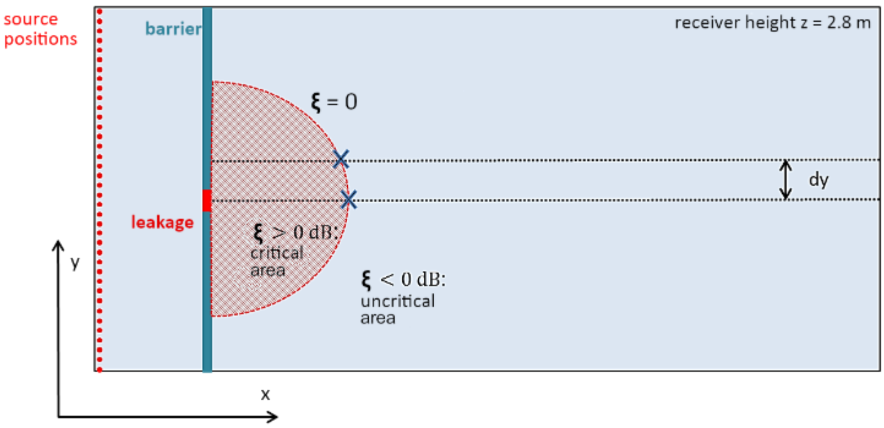

Figure 2: Illustration of the acoustical critical area behind a barrier with a leak ©*BASt*

As described in D2.2 in detail, the *German guidelines for noise protection at roads* (RLS-90) [7] are used and extended in order to model the transmission through a barrier induced by a leak. In short, the general idea is that the leak is regarded as a point source which is “fed” by a line source (road). This point source emits a hemispherical sound wave into the area behind the barrier. The sound power of its contribution is reduced according to the transmission loss caused when passing through the barrier.

The contributions to $L_{m,b}$ and $L_{m,t}$ are stated in the report of D2.2 (cf. Sections 2.2.1 and 2.2.2 in [4]). Inserting all expressions from the RLS-90 and exploiting the underlying geometry above, $L_{m,b}$ and $L_{m,t}$ read as follows:

$$\boldsymbol{L_{m,b} = L_{m,E} + 15,8 - 10 \cdot lg[s_k] - 7 \cdot lg\left[5 + \frac{70 + 0,25 \cdot s_k}{1 + 0,2 \cdot z} \cdot z\right]} \tag{3}$$

$$\boldsymbol{L_{m,t} = L_{m,E} + 15,8 - 10 \cdot lg[s_L] + 10 \cdot lg[S_L \cdot \tau] + 3.2 - 20 \cdot lg[s_{L,k}] - \frac{s_{L,k}}{200}} \tag{4}$$

Here, apart from the geometric measures described in Figure 1, $L_{m,E}$ is the emission level of the source, $z = a + b - s_k$ is the detour of the sound passing via the barrier edge (compared to the direct path s_k from source to receiver), S_L is the effective area of the leak and τ is the transmission coefficient describing the sound transmission loss through the leak. With equation (3) and (4), the criticality condition (2) becomes:

$$\begin{aligned} 10 \cdot lg[S_L \cdot \tau] + 13.2 - 20 \cdot lg[s_{L,k}] - \frac{s_{L,k}}{200} - 10 \cdot lg[s_L] \\ = -10 \cdot lg[s_k] - 7 \cdot lg\left[5 + \frac{70 + 0,25 \cdot s_k}{1 + 0,2 \cdot z} \cdot z\right] \end{aligned} \tag{5}$$

Simple trigonometry allows to express s_k, $s_{L,k}$ and z by the perpendicular distance d_k from noise barrier to receiver (compare Figure 1):

$$\boldsymbol{s_{L,k} = \sqrt{d_k^2 + (h_L - h_k)^2}} \tag{6}$$

$$\boldsymbol{s_k = \sqrt{\left(h_k - h_Q\right)^2 + \left(d_k + d_Q\right)^2}} \tag{7}$$

$$\boldsymbol{z = a + b - s_k = \sqrt{d_Q^2 + \left(h_{NB} - h_Q\right)^2} + \sqrt{d_k^2 + (h_{NB} - h_k)^2} - s_k} \tag{8}$$

Thus, the problem is reduced to one unknown variable and equation (5) can be solved numerically.

As for the underlying geometry, also for this simplified calculation it should be emphasized that it cannot substitute measurements, because it relies on several assumptions and does have a large uncertainty. Instead, it yields a first estimation of the acoustical consequences of a leak and suggests where it is advisable to measure.

3.7.3 Superposition of leaks

All considerations above are formulated for the case of a single leak in a noise barrier. Yet, generally, more than one damage can occur at a noise barrier. Several leaks might be located within the same noise barrier field (e.g. horizontal acoustic elements with missing sealings one above the other) or close to one another, affecting neighbouring noise barrier fields.

In these cases, the critical radius and acoustic rating calculated for an individual leak is of limited significance. On the one hand, it describes the severity of the single leak and gives a measure for the *acoustic* degradation due to this specific leak, on the other hand it does <u>not</u> yield a correct overall *acoustic* assessment at the respective noise barrier field if surrounding leaks are not considered.

To close this gap in the *acoustic* assessment, a superposition of the effect from several neighbouring leaks is carried out. Since this is not a trivial summation of the individual critical radii, some preliminary considerations and analyses had to be performed first:

1. *How does the critical radius scale with the effective area S_L of the leak?*

   There is a linear dependence between the critical radius and the effective area S_L of the leak. In very good approximation the critical radius doubles for a doubling of S_L.

2. *How strongly does the critical radius change with varying height h_L of the leak?*

The dependence of the critical radius on the height h_L of the leak is only weak. A variation of $\Delta h_L = 4$ m changes the critical radius by less than 10%. The effect becomes even weaker the smaller the considered damage is.

3. *Is it possible to theoretically condense two leaks at the <u>same horizontal position</u> within the same noise barrier field (but of different heights h_L) into one leak located in between (with a correspondingly larger effective area S_L)?*

   The analyses showed that modelling the acoustic effect of two leaks at the same horizontal position by substituting them by one leak located in between (with a correspondingly larger effective area S_L) represents a very good approximation. In average, the substitution led to a very slight overestimation of the critical radius of about 4%.

4. *Is it possible to theoretically condense two leaks at the <u>same vertical position</u> within the same noise barrier field (but with a certain horizontal distance x to one another) into one leak located in between (with a correspondingly larger effective area S_L)?*

   The analyses showed that modelling the acoustic effect of two leaks at the same vertical position by substituting them by one leak located in between (with a correspondingly larger effective area S_L) leads to nearly negligible differences and represents a fairly good approximation. In average, the substitution led to a minor overestimation of the critical radius of less than 1%.

5. *How does the transmitted sound level $L_{m,t}^{(0)}$ through a single leak compare to the transmitted sound level $L_{m,t}^{(1)+(2)}$ passing through two neighbouring leaks (symmetrically aligned) at the same height h_L?*

   The difference $\Delta L_{m,t}$ between $L_{m,t}^{(1)+(2)}$ and $L_{m,t}^{(0)}$ of course depends on the horizontal distance x between the single "original" leak and the "additional" neighbouring leaks. $\Delta L_{m,t}$ is independent from the effective area of the leak and only very weakly dependent on the height of the noise barrier. The analyses showed that for a distance x of 65 m the difference $\Delta L_{m,t}$ amounts to more than 6 dB. Thus, transmission paths from "additional" leaks which are 65 m or farther away from the considered "original" leak can be neglected.

6. *How do the critical radii of different leaks have to be weighted when calculating their sum for an overall acoustic assessment considering multiple leaks?*

   The critical radius increases, the more leaks are present close to the noise barrier field under consideration. It is intuitively clear that this increase depends on how close the additional leaks are situated: a leak with a critical radius of 20 m in 30 m distance might have a weaker effect than a leak with a critical radius of 10 m in only 15 m distance. In order to approximate the diminishing influence with increasing distance of additional leaks onto the "original" leak, the weighting function for the superposition of the critical radii has been numerically determined for medium sized damages. For this purpose, two cases have been compared: (a) a central leak with two (symmetrically aligned) additional leaks and (b) a singular central leak with an equivalent effective area S_L. The resulting weighting function is depicted in Figure 3 and its values given in Table 1.

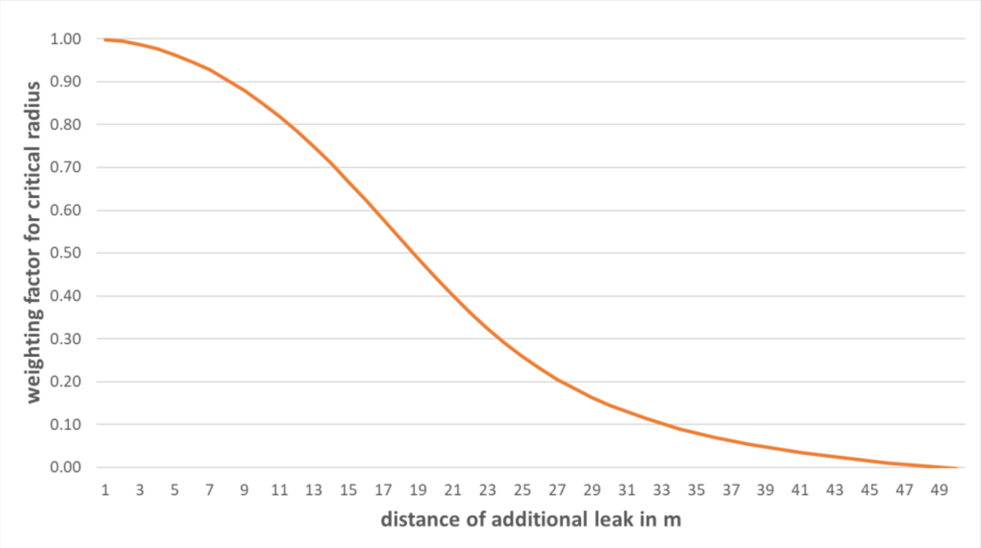

Figure 3: Weighting function for the superposition of the critical radii of different leaks

Table 1: Values of the weighting factor for the superposition of the critical radii of different leaks

distance in m	weighting factor	distance in m	weighting factor
1	1.00	26	0.23
2	0.99	27	0.21
3	0.99	28	0.18
4	0.98	29	0.16
5	0.96	30	0.15
6	0.95	31	0.13
7	0.93	32	0.12
8	0.90	33	0.10
9	0.88	34	0.09
10	0.85	35	0.08
11	0.82	36	0.07
12	0.79	37	0.06
13	0.75	38	0.05
14	0.71	39	0.05
15	0.67	40	0.04
16	0.62	41	0.03
17	0.58	42	0.03
18	0.53	43	0.02
19	0.49	44	0.02
20	0.44	45	0.02
21	0.40	46	0.01
22	0.36	47	0.01
23	0.32	48	0.00
24	0.29	49	0.00
25	0.26	50	0.00

In summary, the following conclusions can be drawn:

The considerations in questions 1. and 2. show that the addition of critical radii is acceptable, i.e. it basically reflects the scaling of the size of the damage. From the analyses in questions 3. and 4. it can be concluded that the critical radii of leaks within the same noise barrier field can be simply summed up to describe their superposition. And finally, the evaluations in questions 5. and 6. allow to correctly weight the critical radius depending on the distance between the leaks.

3.7.4 Implementation into acoustic inspection protocol

From the inputs on the first three *Excel* sheets of the in-situ *acoustic* inspection protocol, all necessary information to solve equation (5) are available:

- The effective area S_L of the leak is calculated from the size ranges given in the 'Defects' sheet. The centre value of each range is used in the product.
- The assumed transmission coefficient τ depends on the choice in the column *view through* in the 'Defects' sheet. For "yes", $\tau = 1$ is assumed; for "no", τ is set to 0.5. This approximation is supposed to be "on the safe side" and overestimates the radius of influence.
- The distance s_L from the emission source to the leak depends on the source height (globally set to 0.5 m), the perpendicular distance d_{NB} between source and noise barrier (globally set to 7.625 m or, if there is no emergency lane, to 5.125 m – see also Section 3.6) and the vertical position of the leak as protocolled in the 'Defects' sheet.

The 'Calculation' sheet (hidden by default) summarizes the general parameters and the parameters specific for each inspected noise barrier field, then calculates all geometric parameters as described above, and eventually evaluates the criticality condition ξ, equation (2), for several values of the perpendicular distance d_k from noise barrier to receiver (up to 100 m in steps of 1 m). The value of d_k, at which ξ is closest to 0, is extracted – this value corresponds to the critical radius. From this the final *acoustic* rating follows for each leak individually (left table in the output sheet 'Acoustic assessment'). The thresholds, up to which the condition is rated as acoustically good, questionable or defective, can be set in the 'Settings' sheet (cf. Section 3.6).

The right table in the output sheet 'Acoustic assessment' yields the result of the superposition of neighbouring leaks as described in Section 3.7.3, or in other words, an estimated overall assessment of the *acoustic condition* of the noise barrier regarding the effect of degradations of the airborne sound insulation. A floating sum over the critical radii is calculated, using the weighting function shown in Figure 3. Herein, the distance between leaks is calculated based on the width of a noise barrier field (4 m by default).

Note: If more than one defect is recorded for a noise barrier field, this field formally also occurs more than once in the superposition result. However, the value for the critical radius should be the same in each line and is to be interpreted as one value for the respective field.

4 Testing of the in-situ inspection protocol

In order to be able to practically test the in-situ inspection tool, damages of varying degrees are required for different noise barrier types. Therefore, several road authorities of various federal states of Germany have been contacted to accompany and undertake motorway inspections within Germany. These authorities carry out the regular inspections of road infrastructures, as described in the report on Task T3.1 [3] and assess them using the “SIB-Bauwerke” software. As a result, the inspected noise barriers obtain a condition score, reflecting the condition of the three criteria *stability*, *safety* and *durability*. However, the *acoustic* condition is not evaluated within the existing inspection scheme.

Especially with the federal states of Hesse and Baden-Württemberg, a fruitful contact has been established and several noise barriers with “interesting” damages have been identified. The on-site inspections of these noise barriers and the application of the developed in-situ inspection protocol is presented hereafter.

4.1 General remarks

From June to October 2020, BASt carried out *acoustic* in-situ inspections of noise barriers in the federal states of North Rhine-Westphalia, Baden-Württemberg and Hesse. One of these inspections was carried out as part of a planned regular inspection. Long sections of motorways were investigated and searched for damages at noise barriers. Apart from this, we also received information on the specific location of damaged noise barriers from road authorities. We were allowed to accompany one of the regular inspections and carry out the *acoustic* assessment with the inspection protocol developed herein.

On the following pages, examples of real damages, which were assessed during the inspections, are presented. First, photographs of the respective damage are shown. Then the filled in *Excel* sheets of the inspection protocol are listed. As described above, the first two sheets capture the location and structure of the noise barrier, then the damages are entered in the third sheet (position, size and type), and the final sheet yields the assessment of the *acoustic* condition of the noise barrier.

On the one hand, the acoustic assessment in the fourth sheet is given for each individual damage (left) and considering the total influence of neighbouring damages (right), see Section 3.7.3. The severity of the damages is expressed as the critical radius. This defines an approximate area of influence, in which the *acoustic* degradation due to the leak under consideration is significant and relevant. The actual *acoustic* evaluation of the damage is expressed by the colours **red**, **yellow** or **green**. The colour **green** applies for damages with negligible influence on the *acoustic* performance of the noise barrier (regarding airborne sound insulation). The colour **red**, in turn, expresses that the existing damage has a strong influence on the *acoustic* properties and that the full noise protection level is no longer guaranteed. Here, measures must be taken to restore the functionality of the noise barrier. The colour **yellow** expresses that the in-situ evaluation based on visual inspection cannot make a clear statement about the *airborne sound insulation* of the damaged noise barrier. In these cases, the second stage of the *three-stage progressive approach* is called up in order to obtain a better assessment of the damage, namely by using the "quick measurement method", which is being developed in WP 4 of the SOPRANOISE project. When inspecting a noise barrier, the critical radii in the "estimated overall assessment (superposition)" are of interest for understanding the effect on the acoustic performance. However, the left column of the acoustic assessment, i.e. the "assessment for each NB field individually", is mainly decisive for the question where further measurements via the "quick method" must be carried out.

4.2 Acoustic inspection results and discussion

The inspections carried out showed and confirmed that through-holes in noise barriers with a size in the single-digit centimetre range have only minor acoustic consequences, even though they appear to be visually conspicuous. Here, the results obtained with the *acoustic* in-situ inspection protocol confirmed the impressions gathered during the visual and aural inspections. Even at distances of less than one metre, where vehicles driving on the motorway could be seen through the holes, no level increase was perceived aurally compared to the basic noise level (which is usually composed of the sound transmitted through the wall and sound diffracted over the top edge of the noise barrier). Only for holes with a length of 20 cm to 30 cm, level increases could be heard directly behind the noise barrier. But even holes of this larger size, if they occur individually and isolated, have a negligible level-increasing effect at a distance of several metres behind the barrier. Yet, when such damages or defects occur regularly, for example due to subsidence of the soil over several noise barrier fields, they can be perceived aurally and/or evaluated analytically even at greater distances. Therefore, it was challenging to find examples of leaks that cover the range up to relevant level increases for residents, who are located at a distance of 20 m to 50 m behind the noise barrier.

From all *acoustic* in-situ inspections (25 noise barrier sites in total) carried out within the framework of the project, the most conclusive cases have been selected: the following five examples list and describe defects of varying size and/or number, on the basis of which it is possible to discuss the *acoustic* effects on immission locations behind the noise barrier.

The **first example** is summarised in Figure 4 to Figure 7. The photographs of Figure 4 show the timber noise barrier with the concrete plinth. The noise barrier elements are fixed in steel posts. The 100 m long segment was built due to a lane widening and is located on a short bridge near Kornwestheim (near Stuttgart, Baden-Württemberg) on the motorway A 81 in the direction of Stuttgart. A 2 – 4 cm wide slit can be seen between the concrete base and the bridge. Here, either the closure was not completed, or it was intentionally omitted. In discussions with the responsible inspectors, it was noted that even existing closing strips are dismantled, as then less dirt accumulates at this point, or it is easier to remove it. It is also claimed that such a narrow slot behind the wall is not noticeable. This misconception can be contradicted, as will be seen after carrying out the *acoustic* inspection procedure. The data on the location and the construction of the noise barrier is entered in the corresponding first two *Excel* sheets (see Figure 5). After entering the defect for all 15 elements (see Figure 6; here summarised in a single row), the critical radius of each individual element can be read off in the sheet ‘Acoustic assessment’ (Figure 7) on the left, and the estimated overall influence (weighted summed over all 15 noise barrier fields) on the right. What is striking about this type of damage is how the relatively small radii of influence (5 m each) of the individual elements add up to a maximum of 47 m in the superposition. Since the individual influence radii of 5 m obtain the green *acoustic* rating (value below 15 m) and supposedly in sum lead to a significant acoustic degradation (yellow acoustic rating in the superposition), the next stage of the three-stage procedure, the "quick method", should be carried out here, in order to obtain a measurement-based result on the degradation due to the leaks.

Figure 4: Wooden noise barrier with plinth near Kornwestheim (Baden-Württemberg/Germany)

NB inspection protocol
Sheet 1: Location

road name	A81	
near	Kornwestheim	
emergency lane	yes	
from/to km	572.6	572.7
direction	Stuttgart	
from/to coordinates	48.855956	9.123773
	48.855675	9.123585

NB inspection protocol
Sheet 2: Construction

	main construction material	absorbing front?	absorbing back?	material of posts
	wood	yes	no	steel
combined with				
combined with				

Figure 5: Sheets 'Location' and 'Construction' of the *acoustic* inspection protocol, filled in for the wooden noise barrier with plinth near Kornwestheim (Baden-Württemberg/Germany)

NB inspection protocol
Sheet 3: Defects

field no.	NB side	field height /m	defect location	type/cause of defect: impact	deformation	rust	vegetation	degradation	lacking material	view through	position /m: vertical	position /m: horizontal	size /cm: vertical	size /cm: horizontal	additional notes (e.g. on visual/aural impression, absorption material, environmental conditions, general condition, reference to photographs ...)
1-15	front	5	between element and foundation	☐	☐	☐	☐	☐	☑	yes	0.0 - 0.5	middle	< 4	125 - 235	
				☐	☐	☐	☐	☐	☐						

Figure 6: Sheet 'Defects' of the *acoustic* inspection protocol, filled in for the wooden noise barrier with plinth near Kornwestheim (Baden-Württemberg/Germany). Note: In the actual *Excel* sheet it is not possible to enter a range for the field no. Each noise barrier field has to be recorded individually.

NB inspection protocol
Sheet 4: Acoustic assessment

Assessment for each NB field individually: field no.	acoustic condition	critical radius /m	Estimated overall assessment (superposition): field no.	acoustic condition	critical radius /m
1	G	5	1	Q	27
2	G	5	2	Q	32
3	G	5	3	Q	37
4	G	5	4	Q	41
5	G	5	5	Q	44
6	G	5	6	Q	46
7	G	5	7	Q	47
8	G	5	8	Q	47
9	G	5	9	Q	47
10	G	5	10	Q	46
11	G	5	11	Q	44
12	G	5	12	Q	41
13	G	5	13	Q	37
14	G	5	14	Q	32
15	G	5	15	Q	27

Figure 7: Sheet 'Acoustic assessment' of the *acoustic* inspection protocol; result for the wooden noise barrier with plinth near Kornwestheim (Baden-Württemberg/Germany)

The **second example** is summarised in Figure 8 to Figure 11. The photographs of Figure 8 show the noise barrier consisting of plastic elements filled with absorbent material. The noise barrier is located on the A 81 motorway near Asperg (near Stuttgart, Baden-Württemberg) in the direction of Leonberg. The damage is rectangular or triangular in shape and approximately 10 cm x 10 cm in size. The absorption material and the perforated front side facing the road are clearly visible. The damages were found on three elements with two damages each, which are 6 and 18 elements apart. This example shows well how individual defects that are far apart (24 m and 72 m, respectively) affect the overall performance of a noise barrier section. While the 24 m distant elements still slightly influence each other (field no. 119 and 125), they no longer play a role for the 72 m distant field no. 143. Here, only the two defects located within the same noise barrier field add up. Both in the individual and overall assessment (Figure 11, left and right, respectively), the damage is assessed as *acceptable* as far as airborne sound insulation is concerned and no action is necessary yet. Sound absorption should be investigated, in any case, by measurements.

The **third example**, shown in Figure 12 to Figure 15, refers to an approximately 800 m long acrylic glass noise barrier on a bridge of the federal road B 42 near Oberwalluf (ca. 50 km west of Frankfurt, Hesse). Large pieces have broken off at the upper edge of seven elements that are close to each other, some of which are neighbouring elements. The individual radii of influence of the damage, as resulting from the *acoustic* inspection protocol, lie between 5 m and 17 m (Figure 15, left) and, despite the larger size of the damage, are still rated as green. This is mainly due to the fact that the damages are located at the upper edges of the elements, which effectively “only” represents a slightly lower noise barrier in terms of its effective height. However, due to the fact that most of the elements are close to each other, the critical radii add up to a maximum of 48 m in the superposition and, thus, still do not reach the "red zone", which starts at an influence radius of 50 m as defined in the sheet ’Settings’. This third example is also a good example of the fact that not only *acoustic* concerns are decisive when inspecting a noise barrier. In the case of the damage inspected here, carrying out a repair by replacing the acrylic glass elements might be not sufficient and more extensive maintenance might be advisable due to three further reasons: the damage characteristic indicates that the construction and building work should be examined. The many identical break-outs at the upper edge of the wall elements indicate that they were caused by temperature-related material expansion or shrinkage and/or vibrations from passing heavy trucks. In order to prevent a recurrence of this damage, not least for sustainability and monetary reasons, the design and construction of the element supports at the posts should be critically examined. In addition to that, the graffiti on the barrier elements can also have consequences for the *acoustical* perception, which might not be reflected by the in-situ inspection or even measurements, but only in a psychoacoustic context.

With the **fourth example**, shown in Figure 16 to Figure 19, of a noise barrier on the federal road B 297 near Schlierbach (Baden-Württemberg), we consider a damage at the transition between the lowest noise barrier element and the foundation. The noise barrier consists mainly of fields with aluminium cassettes on a concrete plinth, which are interrupted by concrete elements. Due to a lowering of the ground, slits of an average width of about 10 cm and 20 cm, respectively, were created under the plinth elements of two NB fields. Considered individually, the slits cause a relevant increase in the sound pressure level behind the noise barrier in an area of influence of 7 m and 8 m radius, respectively. Considered together, the critical radius is 15 m, i.e. they simply add up because they are located on directly neighbouring fields. The resulting acoustic rating is green. Even though the slits have a relatively large extent, a degradation of the airborne sound insulation is only significant in the proximity of the two defective noise barrier fields.

Figure 8: Plastic noise barrier near Asperg (Baden-Württemberg/Germany)

NB inspection protocol
Sheet 1: Location

road name	A81	
near	Asperg	
emergency lane	yes	
from/to km	51.4	52.9
direction	Leonberg	
from/to coordinates	48.904998	9.154241
	48.904875	9.154188

NB inspection protocol
Sheet 2: Construction

	main construction material	absorbing front?	absorbing back?	material of posts
	plastics	yes	no	steel
combined with				
combined with				

Figure 9: Sheets 'Location' and 'Construction' of the *acoustic* inspection protocol, filled in for the plastic noise barrier near Asperg (Baden-Württemberg/Germany)

NB inspection protocol
Sheet 3: Defects

field no.	NB side	field height /m	defect location	type/cause of defect: impact	deformation	rust	vegetation	degradation	lacking material	view through	position /m: vertical	position /m: horizontal	size /cm: vertical	size /cm: horizontal	additional notes (e.g. on visual/aural impression, absorption material, environmental conditions, general condition, reference to photographs …)
143	front	2	at element	☐	☐	☐	☑	☑	☑	yes	1.0 - 1.5	right	15 - 35	4 - 8	
143	front	2	at element	☐	☐	☐	☑	☑	☑	yes	1.0 - 1.5	right	4 - 8	8 - 15	
125	front	2	at element	☐	☐	☐	☑	☑	☑	yes	0.5 - 1.0	middle	< 4	< 4	
125	front	2	between elements and post	☐	☐	☐	☑	☑	☑	yes	0.0 - 0.5	left	< 4	8 - 15	
119	front	2	at element	☐	☐	☐	☑	☑	☑	yes	0.0 - 0.5	middle	4 - 8	4 - 8	
119	front	2	at element	☐	☐	☐	☑	☑	☑	yes	0.0 - 0.5	left	< 4	< 4	
				☐	☐	☐	☐	☐	☐						

Figure 10: Sheet 'Defects' of the *acoustic* inspection protocol, filled in for the plastic noise barrier near Asperg (Baden-Württemberg/Germany)

NB inspection protocol
Sheet 4: Acoustic assessment

Assessment for each NB field individually

field no.	acoustic condition	critical radius /m
119	G	1
119	G	1
125	G	1
125	G	1
143	G	1
143	G	1

Estimated overall assessment (superposition)

field no.	acoustic condition	critical radius /m
119	G	3
119	G	3
125	G	3
125	G	3
143	G	2
143	G	2

Figure 11: Sheet 'Acoustic assessment' of the *acoustic* inspection protocol; result for the plastic noise barrier near Asperg (Baden-Württemberg/Germany)

Figure 12: Transparent noise barrier on a bridge near Oberwalluf (Hesse/Germany)

NB inspection protocol
Sheet 1: Location

road name	B42	
near	Oberwalluf	
emergency lane	yes	
from/to km	45.7	46.5
direction	Frankfurt	
from/to coordinates	50.044433	8.137693
	50.044482	8.137751

NB inspection protocol
Sheet 2: Construction

	main construction material	absorbing front?	absorbing back?	material of posts
	acrylic glass	no	no	steel
combined with				
combined with				

Figure 13: Sheets 'Location' and 'Construction' of the *acoustic* inspection protocol, filled in for the transparent noise barrier on a bridge near Oberwalluf (Hesse/Germany)

NB inspection protocol
Sheet 3: Defects

field no.	NB side	field height /m	defect location	type/cause of defect: impact	deformation	rust	vegetation	degradation	lacking material	view through	position /m: vertical	position /m: horizontal	size /cm: vertical	size /cm: horizontal	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	
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	
84	front	2	at element	☑	☐	☐	☐	☐	☑	yes	1.5 - 2.0	middle	15 - 35	125 - 235	
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	
89	front	2	at element	☑	☐	☐	☐	☐	☑	yes	1.5 - 2.0	middle	35 - 65	125 - 235	
				☐	☐	☐	☐	☐	☐						

Figure 14: Sheet 'Defects' of the *acoustic* inspection protocol, filled in for the transparent noise barrier on a bridge near Oberwalluf (Hesse/Germany)

NB inspection protocol
Sheet 4: Acoustic assessment

Assessment for each NB field individually: field no.	acoustic condition	critical radius /m	Estimated overall assessment (superposition): field no.	acoustic condition	critical radius /m
35	G	5	35	G	5
57	G	9	57	G	9
83	Q	17	83	Q	39
84	G	8	84	Q	44
86	G	5	86	Q	48
87	G	9	87	Q	46
89	Q	17	89	Q	38

Figure 15: Sheet 'Acoustic assessment' of the *acoustic* inspection protocol; result for the transparent noise barrier on a bridge near Oberwalluf (Hesse/Germany)

Figure 16: Aluminium-cassette noise barrier with plinth near Schlierbach (Baden-Württemberg/Germany)

NB inspection protocol
Sheet 1: Location

road name	B297	
near	Schlierbach	
emergency lane	no	
from/to km	29.9	30.8
direction	Albershausen	
from/to coordinates	48.673994	9.512251
	48.673886	9.512334

NB inspection protocol
Sheet 2: Construction

	main construction material	absorbing front?	absorbing back?	material of posts
	aluminium	yes	no	steel
combined with	aluminium	yes	no	concrete
combined with				

Figure 17: Sheets 'Location' and 'Construction' of the *acoustic* inspection protocol, filled in for the aluminium-cassette noise barrier with plinth near Schlierbach (Baden-Württemberg/Germany)

NB inspection protocol
Sheet 3: Defects

field no.	NB side	field height /m	defect location	type/cause of defect: impact	deformation	rust	vegetation	degradation	lacking material	view through	position /m: vertical	position /m: horizontal	size /cm: vertical	size /cm: horizontal	additional notes (e.g. on visual/aural impression, absorption material, environmental conditions, general condition, reference to photographs …)
22	front	2	between element and foundation	☑	☐	☐	☐	☐	☑	yes	0.0 - 0.5	middle	15 - 35	125 - 235	
23	front	2	between element and foundation	☑	☐	☐	☐	☐	☑	yes	0.0 - 0.5	middle	8 - 15	235 - 415	
				☐	☐	☐	☐	☐	☐						

Figure 18: Sheet 'Defects' of the *acoustic* inspection protocol, filled in for the aluminium-cassette noise barrier with plinth near Schlierbach (Baden-Württemberg/Germany)

NB inspection protocol
Sheet 4: Acoustic assessment

Assessment for each NB field individually

field no.	acoustic condition	critical radius /m
22	G	8
23	G	7

Estimated overall assessment (superposition)

field no.	acoustic condition	critical radius /m
22	G	15
23	G	15

Figure 19: Sheet 'Acoustic assessment' of the *acoustic* inspection protocol; result for the aluminium-cassette noise barrier with plinth near Schlierbach (Baden-Württemberg/Germany)

The **fifth example** shows a large damage to a noise barrier consisting of plastic elements, probably caused by a strong impact, and is summarised in Figure 20 to Figure 23. The main defect has the dimensions 20 cm x 2 m and leads to a significant area of influence with a critical radius of 32 m behind the noise barrier. The impact caused a second defect in the same field, which extends from the location of the main defect upwards to the upper edge of the noise barrier. At 27 m this defect also has a similarly large radius of influence as the main defect. Together, this results in a critical radius of 59 m. This means that the *acoustic* rating for airborne sound insulation enters the “red zone” and should be repaired as soon as possible.

Summarising the experience of the *acoustic* inspections carried out for testing the in-situ inspection protocol, the following can be stated from the examples considered:

- Small but clearly visible defects could lead to *acceptable acoustic condition* at usual distances behind the barriers.
- For a single (isolated) defect to have a relevant influence on the *acoustic* performance of a noise barrier, a relatively large defect size must be present.
- In the case of several defects, not too far apart from each other and each of a small cross-sectional area, a decrease of the *acoustic* performance of the noise barrier can be expected. Further actions, i.e. either measurements (using the “quick method”) or repairs, can become necessary.

Figure 20: Plastic noise barrier near Rodgau (Hesse/Germany)

NB inspection protocol
Sheet 1: Location

road name	B45	
near	Rodgau	
emergency lane	yes	
from/to km	107.0	107.5
direction	Dieburg	
from/to coordinates	50.009051	8.897331
	50.008208	8.897556

NB inspection protocol
Sheet 2: Construction

main construction material	absorbing front?	absorbing back?	material of posts
plastics	yes	yes	steel
combined with			
combined with			

Figure 21: Sheets 'Location' and 'Construction' of the *acoustic* inspection protocol, filled in for the plastic noise barrier near Rodgau (Hesse/Germany)

NB inspection protocol
Sheet 3: Defects

field no.	NB side	field height /m	defect location	type/cause of defect: impact	deformation	rust	vegetation	degradation	lacking material	view through	position /m: vertical	position /m: horizontal	size /cm: vertical	size /cm: horizontal	additional notes (e.g. on visual/aural impression, absorption material, environmental conditions, general condition, reference to photographs …)
43	front	5	at element	☑	☑	☐	☑	☑	☑	yes	1.5 - 2.0	middle	15 - 35	125 - 235	
43	front	5	between element and post	☑	☑	☐	☑	☑	☐	yes	3.0 - 3.5	left	235 - 415	8 - 15	
				☐	☐	☐	☐	☐	☐						

Figure 22: Sheet 'Defects' of the *acoustic* inspection protocol, filled in for the plastic noise barrier near Rodgau (Hesse/Germany)

NB inspection protocol
Sheet 4: Acoustic assessment

Assessment for each NB field individually			Estimated overall assessment (superposition)		
field no.	acoustic condition	critical radius /m	field no.	acoustic condition	critical radius /m
43	Q	32	43	D	59
43	Q	27	43	D	59

Figure 23: Sheet 'Acoustic assessment' of the *acoustic* inspection protocol; result for the plastic noise barrier near Rodgau (Hesse/Germany)

5 Conclusions

The main goal of Task T3.2 is to provide an *acoustic* in-situ inspection procedure that allows simplified *acoustic* assessments of possible degradations of the airborne sound insulation mainly based on visual inspections and characterisation of defects in a noise barrier. This inspection procedure is supposed to be the first step in the *progressive approach* pursued in the SOPRANOISE project. Nevertheless, it is relevant to note that the inspection tool described here is not intended to be used for approval of newly built noise barriers, as this can occur only if <u>quantitative</u> measurements are performed. The inspection tool does <u>not</u> yield quantitative values of the sound insulation and therefore cannot be used to assess a noise barrier. Its intended purpose is to be used only to prioritize the maintenance of already installed noise barriers. In the first part of the report, the development approach and demands on the inspection method have been presented. Based on the review of existing inspection methods for noise barriers and the answers to the questionnaire in the report on Task 3.1 [3], a profile of requirements for the in-situ inspection method is defined. The criteria motivate the structure and working principle of the resulting *acoustic* inspection protocol.

The *acoustic* inspection protocol is set up as *Excel* file consisting of five different sheets, which are described in detail in Section 3, including the functionality of each input and output field. The main features are:

- interactive handling on site possible (during a general inspection routine by using a portable device)
- minimal inputs; frequent use of dropdown lists or check boxes for a faster and easier handling
- adjustable global settings
- immediate result of the acoustic assessment in a self-explanatory “traffic light” rating and a critical radius; single output sheet
- two types of *acoustic* assessment of airborne sound insulation: individually for each noise barrier field, reflecting the severity of a single leak, and comprehensive <u>overall</u> *acoustic* assessment of possible degradations of the airborne sound insulation, considering the superposition of leaks close to each other

Although the calculations within the framework of the *acoustic* inspection protocol have a clear approximative character, they are based on the theoretical model described in the SOPRANOISE deliverable D2.2 [4] and are able to yield a relevant first estimation of the *acoustic* performance of a noise barrier under inspection regarding possible degradations of the airborne sound insulation without undertaking actual measurements. The most important information follows directly from the “traffic light” rating: a **green** rating states that the noise barrier is in an *acceptable acoustic condition* and no further actions are required regarding its airborne sound insulation; a **red** rating is a clear indication of a *defective acoustic condition*, which has to be repaired in any case; and all cases in between with a **yellow** rating cannot be decided via inspection only. Here, *acoustic* <u>measurements</u> are necessary to define further actions – i.e. in the progressive approach pursued in the SOPRANOISE project, the quick method (as developed in WP 4) has to be applied. When degradations of the *sound absorption* performance are suspected, *sound absorption measurements* must be carried out because the in-situ inspection tool cannot draw quantitative conclusions about it.

In other words, the *acoustic* in-situ inspection procedure provides a valuable method to check where reliable measurements of airborne sound insulation should be done. The inspection protocol should <u>never</u> be applied in place of measurements, because of the uncertainties arising from the simplified assumptions. Moreover, when degradations of the *sound absorption* performance are suspected, *sound absorption measurements* at representative sites must be done, and a preliminary visual inspection may help in selecting these sites. Thus, preliminary in-situ inspections are a great help in pointing out where relevant sound insulation defects may be located, employing only non-acoustically trained personnel moving along the full span of a noise barrier. Then, more skilled personnel should apply the quick measurement method in several selected locations and give a first quantitative assessment of both airborne sound insulation and sound absorption. Finally, a definitive and reliable assessment is given applying the full measurement method according to EN 1793-5 and EN 1793-6 in few selected locations. In this last two steps (the quick method and the measurements according to the standards), skilled operators are required.

The consideration of the superposition effect turned out to be of great importance. In cases with more than one leak within the same noise barrier field or close to each other over different noise barrier fields, an acoustic rating <u>must</u> consider the overall effect to yield reasonable results. In fact, single leaks, even of larger sizes, might have only minor *acoustic* consequences if they occur “alone”. On the other hand, several smaller leaks occurring close to each other might diminish the *acoustic* performance of the noise barrier significantly. The mutual influence of leaks decreases with increasing distance, of course; however, even leaks with about 30 m distance to each other cannot be considered to be fully independent (cf. weighting function in Figure 3).

Degradation effects related to sound absorption properties of a noise barrier are not explicitly considered by the *acoustic* in-situ inspection protocol. These effects are much harder to generalise in calculations and mostly relevant in special cases under specific conditions (cf. scenario calculations in the report on deliverable D2.2 [4]). Because of that, an inspector should be instructed to note any important information about damages on absorption material in the free text field of the in-situ inspection protocol. Depending on the severity of the damage and the surroundings in the vicinity of the noise barrier, it is advisable to apply at least the quick measurement method (see WP4) to ascertain the entity of the damage.

It should be stressed once more, that inspection tools in general are not restricted to the *acoustic* domain. A full inspection will always consider acoustic AND non-acoustic properties. Inspectors will not investigate a noise barrier to assess the *acoustic* behaviour only. The in-situ inspection protocol presented here is therefore supposed to be an add-on to an existing inspection procedure, depending on the handling in the respective country.

In a practical testing phase, German road authorities have been contacted to accompany motorway inspections and apply the *acoustic* in-situ inspection protocol. The tests involved noise barriers of different conditions (both structural and acoustic) and of different materials. Focus of the testing were the basic applicability and the question, how different degrees of (real) damages are assessed by the proposed *acoustic* rating. The behaviour mentioned above could be confirmed: isolated leaks, even of larger size, supposedly have only minor effects on the acoustic performance of a noise barrier. However, the effect of several leaks – even of smaller size – lying close to each other superimposes and might lead to a significant loss of the airborne sound insulation properties of a noise barrier.

All in all, the developed *acoustic* in-situ inspection protocol has proven to yield a clear and realistic approximation of the degradation effect in the airborne sound insulation of a noise barrier due to leaks. In the next and final Task T3.3 of WP 3, the remaining steps on the way towards a fully functional *acoustic* in-situ inspection procedure will be carried out. This includes

- modifications and improvements of the inspection protocol based on feedbacks and experiences e.g. from the PEB,
- the composition of documents for end-user application, i.e. a simplified description of the method, a manual for the *Excel* protocol and a reporting-scheme, and
- a comparison of the evaluations according to the in-situ inspection method with the results of in-situ measurements.

6 References

[1] 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.

[2] 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.

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SOPRANOISE

T3.3 report – Description of the in-situ inspection tools and reporting

May 2021

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1 Introduction

The present report represents the finalisation of WP 3 of the SOPRANOISE project. The goal and main outcome of WP 3 is an in-situ *acoustic* inspection procedure for existing noise barriers, which allows to obtain first indications on the possible effect of degradations of the *airborne sound insulation* based on approximations and simplified calculations and without carrying out acoustic measurements.

The development of the inspection procedure and its theoretical background have been presented in the second report of WP 3 on Task 3.2 [1]. The resonance on the proposed method and its implementation were largely positive; yet and of course, several feedbacks also revealed room for improvements. Thus, the last step in WP 3 consists of incorporating all feedbacks and creating the improved and final version of the in-situ *acoustic* inspection procedure. Furthermore, the framework to actually apply the in-situ inspection procedure in practice has to be provided.

The present report is structured as follows: In Section 2, the changes and improvements in the implementation of the inspection method compared to the pre-final version of Task 3.2 are summarised in a transparent way. Apart from that, a discussion on the underlying approximation and the limits of the inspection procedure is added. The contents of Section 3 form the basis to build the documents to be handed over to potential users of the in-situ inspection together with the inspection protocol, which is realised as an *Excel* document. On the one hand a short description illustrates how the method works, on the other hand there is a practical step-by-step manual including a concrete example. Finally, in Section 4 a conclusion closes this WP with a summary of the potential of the in-situ inspection and its significance within the SOPRANOISE progressive 3-step approach for the (future) acoustic assessment of noise barriers.

2 Final in-situ inspection procedure

2.1 Modifications and improvements

The development and testing of the in-situ inspection procedure were carried out in Task 3.2 of the SOPRANOISE project. The resulting method, the inspection protocol and its validation were presented in the corresponding task report [1]. Based on feedbacks and remarks from the SOPRANOISE consortium and the PEB, marginal modifications and improvements have been applied in a final step. Namely, these are:

- The layout of the *Excel* input and output sheets was slightly modified for a better usability. In addition, each sheet now contains a side header including the most relevant information of the inspection location. This simplifies saving the results in a manageable manner and/or the structured filing of printouts.
- For a better understanding, both the description and the manual of the inspection protocol now include information about the purpose/difference of the input fields "from/to coordinates" and "from/to km" which are part of the sheet 'Location'.
- The possibility to allow the inspector more accurate input values has often been requested, e.g. regarding the height h_k of the receiver position above the ground. However, within the accuracy of the method it is not expedient to allow exact inputs in all cases. The potential as well as the limits of the approximation are now clearly stated hereafter in Section 2.2, and will also be explicitly mentioned in the short description, Section 3.1.
- As explained in the report on Task 3.2 [1], it is recommended to adjust the value for the assumed noise barrier width in the 'Settings' sheet, if the widths of the inspected noise barrier elements are significantly smaller or larger. To be more specific in the final description, this has been analysed more systematically. Varying the barrier field width for different leak sizes showed that for variations larger than ±0.5 m the error in the calculated critical radii (after superposition) exceeds ±10%. This is independent from the assumed leak sizes. Consequently, we recommend to manually set the value for noise barrier widths larger than 4.5 m and smaller than 3.5 m.
- A brief statement on the transferability of the in-situ inspection method to noise barriers near railroads is included in the short description, Section 3.1.
- It is of upmost importance that the intended use of the in-situ inspection tool is clearly constituted. To ensure this and avoid misinterpretations of the acoustic rating obtained with the inspection protocol, a clear scope has been framed. This scope defines the purpose of the in-situ inspection tool and its role within the SOPRANOISE 3-step progressive approach. Moreover, it states how the qualitative inspection results have to be understood. This scope is part of the short description.

2.2 Notes on approximation and its limits

The goal of designing an *acoustic* in-situ inspection procedure was to offer a method, which evaluates the loss of the acoustic performance of a noise barrier induced by leaks – and this with only minimal input information, obtainable without measurements but only by visually inspecting the noise barrier. Such an inspection procedure, inherently, cannot provide *quantitative* results on the *intrinsic acoustic properties* of a noise barrier: instead, it (a) targets to deliver a quick but relevant *qualitative* estimation of the effect of degradation on the insertion loss of the noise barrier (which is an *extrinsic characteristic*), and (b) therefore has to rely on several simplifying assumptions to keep it simple and applicable on site.

The approximative calculations of the critical radii and acoustic rating given in the inspection protocol are based on the theoretical model described in the SOPRANOISE report on deliverable D2.2 [2]. The general idea of this approach is to compare the sound diffraction across the top edge of the noise barrier with the sound transmission through a leak in the noise barrier. If the difference between these two contributions exceeds 10 dB, the criticality condition is fulfilled and the presence of the leak has no significant influence on the sound immission level behind the barrier.

Essentially, the approximations comprise the following aspects:

- A two-dimensional description is chosen.
- Only one lane (closest to the noise barrier) is considered as *emission sound source.*
- The geometry is mostly fixed, i.e. source/receiver heights and distance between emission sound source and noise barrier.
- The position of the leak does not require an exact input by the inspector, but a selection of matching ranges.
- A leak with full view through is assumed to have full transmission, i.e. the sound insulation is fully reduced at the leak position. For an only partly translucent damage the insulation is assumed to be halved.
- The non-damaged parts of the barrier are assumed to be fully insulating.

All these simplifications underline the *qualitative* character of the model: it is simplified in such a way that it becomes quickly applicable on site, but only so far that a clear and realistic approximation of the degradation effect due to leaks still can be obtained. This balance between practical applicability and quality of the approximation is achieved by choosing the most relevant input parameters for the inspection, specify input ranges and/or using default values and fixing the geometric conditions wherever feasible.

The question of accuracy always has to be kept in mind in this context. The input of the actual distance to the first lane, the receiver height or other similar parameters might be relevant if an <u>exact</u> reproduction of the situation on site is aimed at, but it also adds additional 'measurements' to be performed during the in-situ inspection and creates the 'illusion' of a high accuracy which is not given within the approximation of the model. In the end, the result of the *acoustic inspection* is supposed to yield a first approximate estimation about the possible degradation of the airborne sound insulation of a noise barrier without carrying out actual *acoustic* measurements.

2.3 Practical testing

In addition to the practical testing carried out in the development process (see [1]) of the in-situ inspection method, further testing is supposed to be performed in order to establish the connection between the evaluations according to the in-situ inspection method with the results of in-situ measurements. This in particular includes conclusions on the indications, coming from the inspection method, about the preferred locations where to apply acoustic measurements via the quick measurement method developed in WP4; but also, the relation to the full measurement procedure according to EN 1793-5 [3] and EN 1793-6 [4].

For this purpose, it is planned to apply the in-situ inspection method in the same places where the quick method will be validated. Since this validation of the quick method (Task 4.3 of WP4) is going to be carried out later in 2021, the results on the mutual application of all three steps of the progressive 3-steps approach will be included in the deliverable "D4.2 Quick & safe methods alongside roads".

3 Documents for end-user application

In the following, two descriptive sections explaining the use of the *acoustic* in-situ inspection method are provided. Together with the *Excel* protocol file, the short description (Section 3.1) and the manual (Section 3.2) constitute all relevant information for the application of the inspection procedure. Potential inspectors should always have access to the full set of those three documents to ensure a regular execution of the method and a correct understanding of the results.

3.1 Short description of in-situ inspection procedure

Scope

The acoustic in-situ inspection represents the first step of the **SOPRANOISE progressive 3-step approach** (Figure 1) for the assessment of the acoustic performance of noise barriers. This approach provides a systematic way for the acoustic characterization of noise barriers, independent from the noise barrier age.

In-situ inspections require minimal effort and are mainly based on visual checks. No acoustic measurements are carried out in this step. Therefore, the results have only limited accuracy; yet, they work fairly well to obtain a first rough qualitative picture of the noise barrier's acoustic condition.

The second stage covers fast and simplified acoustic measurements via the quick in-situ test method. The **quick method** allows to systematically and quantitatively characterize the acoustical properties (airborne sound insulation and sound absorption) of installed noise barriers with medium effort. Its accuracy is high enough to confirm the indications from the in-situ inspections and reliably identify further problematic noise barrier regions.

Maximum accuracy is given in the third step by the known **full in-situ tests** according to the standards EN 1793-5 and -6. These methods allow a full quantitative acoustic characterization of noise barriers, but also require the biggest effort, i.e. skilled operators, careful placement of the equipment and a thorough measurement operation.

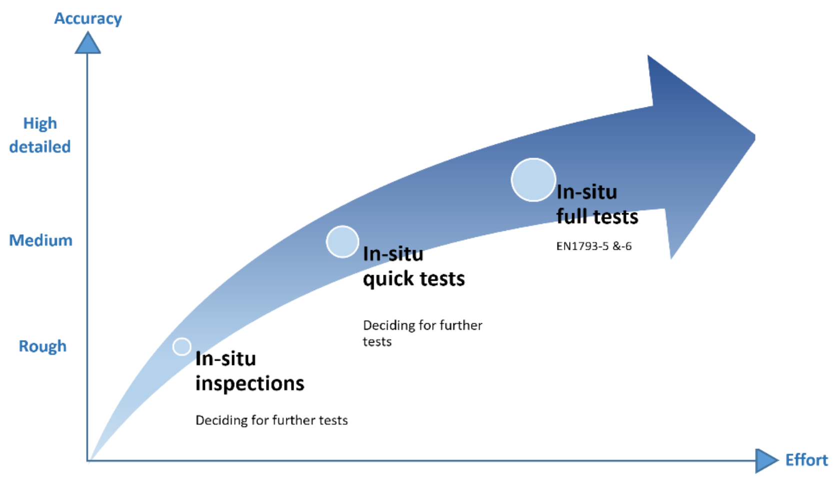

Figure 1: SOPRANOISE 3-step approach for acoustic characterization of noise barriers

The scope of application for the SORPANOISE 3-step approach is summarised in Figure 2. Initially, in all cases, it is necessary to define the reason for the planned noise barrier investigation. For the **approval** of a newly built noise barrier or, more generally speaking, for legal reasons which require quantified values of intrinsic characteristics (DL_{RI} and DL_{SI}), the only way is to carry out measurements according to the EN 1793 standards. Only the EN 1793 measurements represent the legal conformity check with highest possible accuracy.

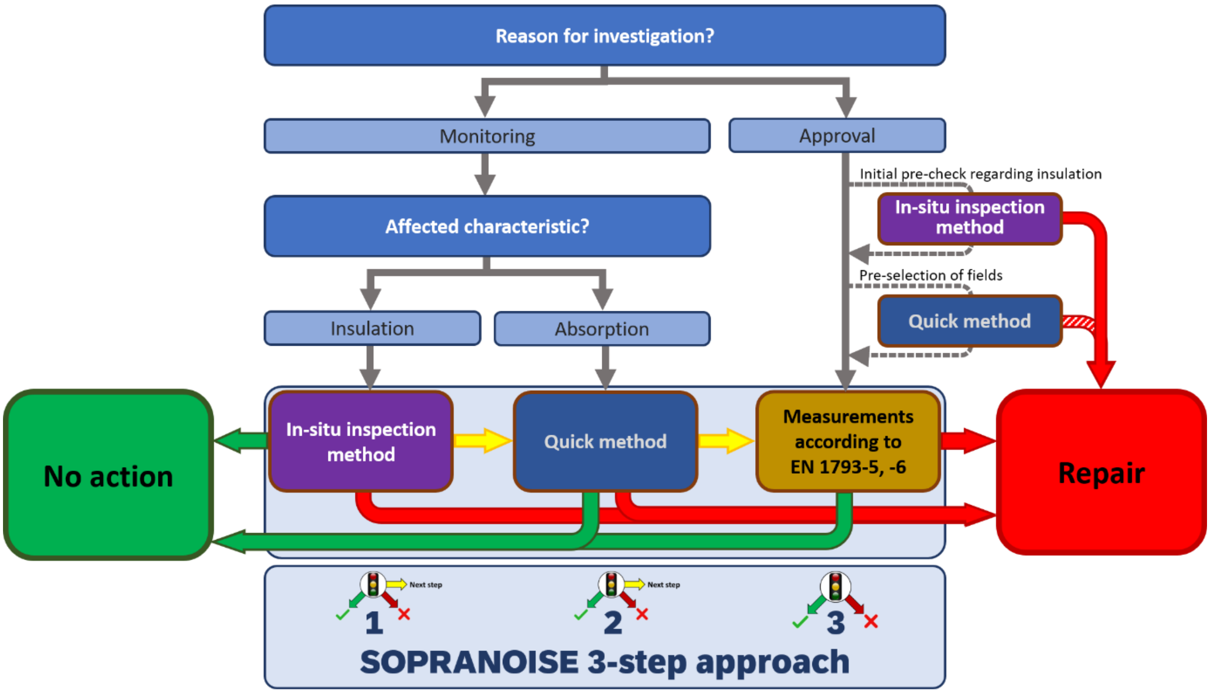

Figure 2: Flow chart visualising the scope of the SOPRANOISE 3-step approach

Since approvals according to the EN 1793 standards can be expensive and time-consuming – especially in the case of long noise barriers – it is advisable to first carry out in-situ inspections and measurements via the quick method. With the in-situ inspection, obvious and apparent defects can be found and directly rejected. Sampling via the quick method also allows a fair pre-selection and relevant locations of a limited amount of tests to be done with the EN1793; in addition, the authority could also decide for rejection at this stage, but then a decisional rule has to be clearly established. This way, the number of full tests is limited and the amount and location of those full tests could be fairly explained / justified.

The 3-step approach comes into action when a noise barrier investigation is planned within a **monitoring** process of an existing noise barrier.

For the evaluation of sound absorption properties, it is necessary to directly make use of acoustic measurements via the quick method (step 2), since it is not possible to draw conclusions about the degradation of sound absorption characteristics from in-situ inspections only.

The purpose of in-situ inspections (step 1) is to obtain useful indications and spot out major defects, in order to deliver a very quick and relevant estimation of the degradation of the insertion loss of the noise barrier, induced by a diminished sound insulation. This facilitates the follow-up monitoring and maintenance of installed noise barriers, considering its insertion loss performance. In-situ inspections do not give a quantitative value of airborne sound insulation.

The acoustic rating obtained via the in-situ inspection method identifies defects with negligible consequences for the insertion loss (**green** rating), defects which surely have to be repaired (**red** rating) and defects which require an actual assessment via acoustic measurements (yellow rating). This establishes the transition to step 2 of the SOPRANOISE 3-step approach, i.e. the quick method.

The quick method fills the gap between in-situ inspections and full testing regarding EN 1793-5 and -6. It gives quantitative conclusions about the acoustic performance of a noise barrier and values for the intrinsic noise barrier properties, airborne sound insulation and sound absorption; and it is designed to be safer, faster, easier to handle and more cost-effective than the full methods. This way, severe degradations for which repairs are surely required, can be located. The main purpose of the quick method is to identify the best sites for the official assessment of a noise barrier and thereby reduce the amount of full measurements according to EN standards. Its accuracy is not comparable to that of EN standards, however, the results show high and useful correlations.

The SOPRANOISE 3-step approach optimises the assessment of the acoustic performance of noise barriers by exploiting a progressive evaluation strategy. The different stages of the method come into play under the conditions described above and thereby help to realise much more systematic tests, improve the understanding of acoustic performance losses and consequently the sustainability of noise barriers. However, it is important to note that neither the in-situ inspection procedure nor the quick method can substitute the conformity test according to the EN 1793 standards.

Functionality

The *acoustic* in-situ inspection procedure is an easy-to-use method to approximate the degradation effect on the acoustic performance of a noise barrier. The assessment focusses on the possible effect on *sound transmission* and the *insertion loss*. It is based on inputs which can be made by visually inspecting a noise barrier and protocol the size and position of identified defects. No *acoustic* measurements are required.

The inspection result distinguishes between a *defective acoustic condition* (**red** condition) and an *acceptable acoustic condition* (**green** condition) and points out leaks which require a further *acoustic analysis* (**yellow** condition) via the SOPRANOISE quick measurement method and/or the full method according to the standard EN 1793-6 [4].

If degradations of the *sound absorption* performance are suspected, an inspection is not sufficient. Quantitative measurements must be carried out with the SOPRANOISE quick measurement method and/or the full method according to the standard EN 1793-5 [3].

Theoretical background

The calculations in the in-situ inspection protocol are based on a simplified theoretical model. The simplifications and approximations of the model involve several acoustical assumptions (e.g. only the traffic lane closest to the barrier is considered as emission source and the leak is modelled as a point source) and the source-barrier-receiver geometry is fixed as much as possible. Then, the sound diffraction across the top edge of the noise barrier is compared with the sound transmission through a leak in the noise barrier. The difference is a measure for how strongly the airborne sound insulation is affected by the identified damage. The larger the difference, the more dominant is the contribution from sound diffraction and the less relevant the presence of the leak. This way, a critical area (given by the critical radius) behind the noise barrier is defined and calculated: herein, the influence from the leak on the sound immission level is significant.

In order to account for the fact that more than one leak might be located within the same noise barrier field or close to one another, the model is furthermore extended with an *overall acoustic assessment*. This considers the superposition effect for leaks located within a certain range. Depending on the distance between the leaks, the individual critical radii are weighted and summed up. In cases with more than one leak, the superposition effect is essential to obtain a realistic and reasonable rating of the acoustic condition.

The theoretical framework has been developed for the application to noise barriers near roads. In principle, a similar procedure can be developed for noise barriers near railroads. Yet, the inspection protocol as it is now cannot be simply applied to railroads. The general approach (i.e. the comparison between diffracted and transmitted sound contributions to calculate a critical area of influence) is transferable, but new calculations are needed within the model to account for different geometries, the different position and number of the sound emission sources and the directivity of the sound emission. Also, assuming a line source to model passing trains might not represent an adequate approximation. All those factors have to be investigated before transferring the in-situ inspection method to railroads.

Approximation

The calculation of the critical radius for a specific leak in a noise barrier as well as the determination of the superposition effect yield a meaningful first *qualitative* results for the degradation effect on the insertion loss of a noise barrier, in the presence of visible leaks. For the correct interpretation of the results, it is important to keep in mind that the in-situ inspection procedure does not intend to (and is not able to!) replace *quantitative* acoustic measurements, as provided by the SOPRANOISE quick method or measurements according to the standards EN 1793-5 and -6. Quantitative measurements will be indispensable, if the evaluation of intrinsic noise barrier properties (i.e. airborne sound insulation or sound absorption) is required.

The input options in the in-situ inspection protocol are limited in a sense that *exact* values for the defect size and position are not required and default values are set for certain global parameters. Within the accuracy of the approximation this is sufficient. Allowing more or more precise inputs does not influence the results of the method significantly.

Structure of the in-situ inspection protocol

When performing a noise barrier inspection on site, the inspector can use the *acoustic* inspection protocol to obtain a first approximation of the acoustic condition of the noise barrier. The protocol file is designed to be easy to understand and handle and requires minimal inputs. After filling in all detected leaks and damages, it immediately returns the result of the evaluation, including the information where acoustic measurements are necessary.

The *acoustic* inspection protocol is set up as *Excel* file consisting of five different sheets. The first three sheets ‘Location’, ‘Construction’ and ‘Defects’ are the input sheets. The fourth sheet ‘*Acoustic* assessment’ is the central output and directly yields an *acoustic rating* in form of a traffic light system. Additionally, a critical radius is included. This value is a measure for how strongly a leak affects the acoustic performance of the noise barrier, and defines the radius up to which a leak has a non-negligible effect. In other words, the larger the critical radius, the larger the performance loss due to the leak.

The fifth sheet ‘Settings’ allows to change certain global parameters, if necessary. The internal calculations are realized in the background and are not visible for the user.

Sheet ‘Location’

The general information about the location of the noise barrier is entered here.

road name	Name of the road on which the noise barrier is located.
near	Name of closest neighbouring city.
emergency lane	The inspector has to select if there is an additional lane in between the noise barrier and the closest traffic lane. This defines the distance between the sound emission and the noise barrier. An exact input of this distance is not necessary. Default values are predefined in the ‘Settings’ sheet, serving as common average values for the two cases. They can be modified if needed (see description of ‘Settings’ sheet below).
from/to km	Inspected road km from the beginning to the end of the noise barrier.
direction	Direction of travel of the inspected noise barrier.

from/to coordinates	GPS coordinates of the beginning and the end of the inspected noise barrier section.

All inputs in the sheet 'Location' – except for the information about the emergency lane – are for identification purposes only and optional. In particular, if the acoustic inspection is implemented in an existing procedure, some of these inputs become obsolete, because they are already protocolled elsewhere. The purpose of the field "from/to km" is to record the inspected length, whereas the field "from/to coordinates" captures the exact position for a better localisation. In general, it is sufficient to fill in one of those two fields.

Sheet 'Construction'

All Information on the materials used in the design of the noise barrier are protocolled here.

main construction material	Main component of the entire noise barrier construction.
combined with	If there are components of other materials, this can be chosen here. E.g. this can be used to protocol the different materials used for the cladding and the barrier itself.
absorbing front/back?	For each material used, it can be specified whether the front and/or the back side is sound absorbing or not.
material of posts	The material of the noise barrier posts ["steel", "concrete" or "---" (without posts)] can be chosen here.

The purpose of the 'Construction' sheet is to protocol the basic construction properties. The acoustic assessment itself is independent from the inputs made here, i.e. the inputs do not affect the calculation. Yet, the information might be relevant for further investigations and it is recommended to fill in this sheet.

Regarding sound absorption, it is important to note that at the state of the art it is not possible to generalize and easily describe the acoustic consequences of a degradation in the sound absorption within a theoretical model. If damages in the sound absorbing material are detected and degradations of the *sound absorption* performance are suspected, measurements have to be carried out for quantifying the acoustic consequences.

Sheet 'Defects'

This is the main input sheet of the in-situ *acoustic* inspection protocol. Each row in the table represents a defect that has been identified, containing all information on that defect.

field no.	Number of the noise barrier field with the located defect; only whole numbers are allowed. This can be either an official infrastructure identification number or a running number, counting all noise barrier fields of the inspected road section. It is important that the relative numbering of the noise barrier fields is consistent, since the distance of neighbouring defects is calculated based on this number. In other words, noise barrier fields without defect also have to be considered when counting.
NB side	Side of the noise barrier on which the defect is detected. The selection "front" refers to the unshielded (road) side and "back" means the shielded side behind the barrier; for localisation purposes only.
field height	Height of the noise barrier field with the located defect.
defect location	Describes on which noise barrier component the defect is located; for localisation purposes only.

type/cause of defect	Different defect types and causes describing the appearance of the leak. Multiple selections are possible.
view through	If it is possible to fully look through the leak, the inspector is supposed to select “yes”. For an only partly view through, the selection should be “no”. The choice defines the degree of sound transmission through the leak for the calculation.
position /m, vertical	Vertical position of the defect within the noise barrier field, i.e. height of the defect above ground.
position /m, horizontal	Horizontal position of the defect within the noise barrier field; for localisation purposes only.
size /cm, vertical	Average expansion of the defect in vertical direction.
size /cm, horizontal	Average expansion of the defect in horizontal direction.
additional notes	Additional field for entering comments as free text.

For the sake of a fast and easy inspection process on site, all relevant inputs have to be selected from a dropdown list or via check boxes. It is the inspector’s task to evaluate the defect size as good as possible and choose the best-fitting ranges. If uncertain between two ranges, the lower values should be chosen to avoid strong overestimations of the acoustic degradation.

It is recommended to note any further aspects helpful for subsequent analyses and decisions in the field for additional notes. These can concern e.g. the visual and aural impression on site (i.e. the subjective perception whether the detected leak has an effect on the acoustic performance of the noise barrier or not), the general noise barrier condition, surroundings, or qualitative comments on the absorption material.

Sheet ‘Acoustic assessment’

The result of the *acoustic* inspection is presented in this single output sheet.

Two different types of *acoustic* assessment are included: on the left, the result of the calculation is given for each noise barrier field individually. However, in general more than one leak can occur in the same noise barrier field or in neighbouring noise barrier fields: thus, on the right, an approximated overall *acoustic* assessment due to the superposition of leaks close to each other is given.

field no.	Number of the noise barrier field with the located defect; sorted in ascending order.
acoustic condition	Traffic light rating of the *acoustic condition* based on the inspection inputs made on the first three *Excel* sheets. **Green**: *acceptable acoustic condition*, non-priority actions required for airborne sound insulation. Reminder: no conclusion possible for sound absorption. **Yellow**: *questionable acoustic condition*, further testing could be required for assessing the effective airborne sound insulation (e.g. passing on to quick measurement method). **Red**: *defective acoustic condition* regarding airborne sound insulation, repairing required.
critical radius /m	Calculated 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. The higher the critical radius, the bigger is the acoustically affected area. The value in the left table follows directly and only from

the properties of the corresponding leak. The value in the right table is the result of the superposition of neighbouring leaks.

Sheet 'Settings'

The 'Settings' sheet allows the inspector to change certain global parameters. In general, modifications are not necessary here, since the default values are a good approximation within the accuracy of the method. In order to avoid an incorrect use or accidental changes, this sheet is locked by default. To unlock and edit the sheet, the user simply has to right-click the sheet tab and select "Unprotect Sheet" from the context menu. After changing the settings, it is important to re-activate the sheet protection.

The cases and conditions for which changes might be useful are described below.

size of NB field /m: Size (width) of the inspected noise barrier field; the default value is 4 m. The field size is used to determine the (approximate) distance between defects when calculating their superposition.

If the field size differs significantly, i.e. more than ±0.5 m, this value should be manually adjusted here to obtain a more realistic estimation of the superposition effect.

thresholds for critical radius for colour rating: Thresholds specifying the trigger values of the critical radius for the acoustic traffic light rating. By default, the noise barrier field is assessed to have a *defective acoustic condition* (**red**), if the critical radius exceeds 50 m. A *questionable acoustic* condition (**yellow**) is indicated for values between 15 and 50 m.

The intention of the acoustic rating is to help with the question: what are the next steps in the maintenance of the noise barrier under inspection? Where do repairs or quantitative acoustic measurements become necessary? In general, these default threshold values represent a good compromise for this decision. However, the situation on site and in the surroundings is always different and, eventually, it is up to the inspector to decide. If no residential/sensitive buildings are close by, it might be acceptable to select higher thresholds. On the other hand, if residents are living in close proximity to the noise barrier, stricter values might be required. Therefore, the thresholds can be manually adapted for such specific cases.

distance to first lane with and without emergency lane /m: Distance from the noise barrier to the first traffic lane (emission source). The calculation distinguishes between the case with and without emergency lane (as selected in the 'Location' sheet). In the presence of an emergency lane, the default value is 7.6 m, otherwise 5.1 m.

If the inspected noise barrier is located significantly farther away from the first traffic lane (≥ 10 m) or very close (≤ 4 m), the value should be manually set by the inspector. Smaller deviations, however, are not critical and have no significant effect on the acoustic assessment within the accuracy of the approximation.

3.2 Manual for in-situ inspection protocol

The *Excel* file of the in-situ inspection protocol consists of five sheets. The sheets 'Location' and 'Construction' are intended for the input of the basic noise barrier data. While these first two sheets can be prepared and filled in before the actual in-situ inspection, the third sheet 'Defects' is the main input sheet for the in-situ inspection itself. The fourth sheet 'Acoustic assessment' represents the output sheet indicating the acoustic impact of the detected defects.

The fifth sheet ’Settings‘ contains a few global settings that actually only need to be adjusted under specific conditions. In general, the default values work as a good compromise.

The following manual shows step by step how to fill in the inspection protocol. A concrete example is used for better clarification. The main focus here is on data entry. For more detailed information on the theoretical background or the functionality of individual input fields, please refer to the short description (Section 3.1).

Preparation before inspection

Before performing the actual inspection, the first two sheets of the inspection protocol (‘Location‘ and ’Construction‘) should be filled in with the location data and the information on the material composition of the noise barrier. For practical reasons, this can also be done “in the office” before going on site.

Figure 3: Photograph of the noise barrier, on the basis of which the entries in the inspection protocol are described below

Step 1: Location

On the first sheet of the inspection protocol, all data describing the location of the inspected noise barrier are requested. The example is shown in Figure 4.

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**".

No. 4 and 6 in principle are 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.

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 4: Screenshot of the first input sheet 'Location' with exemplary entries

Step 2: Construction

On the second sheet of the inspection protocol, all relevant data concerning the construction of the noise barrier are requested. The input options are 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 exemplary entries in the 'Construction' sheet are shown in Figure 5.

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.

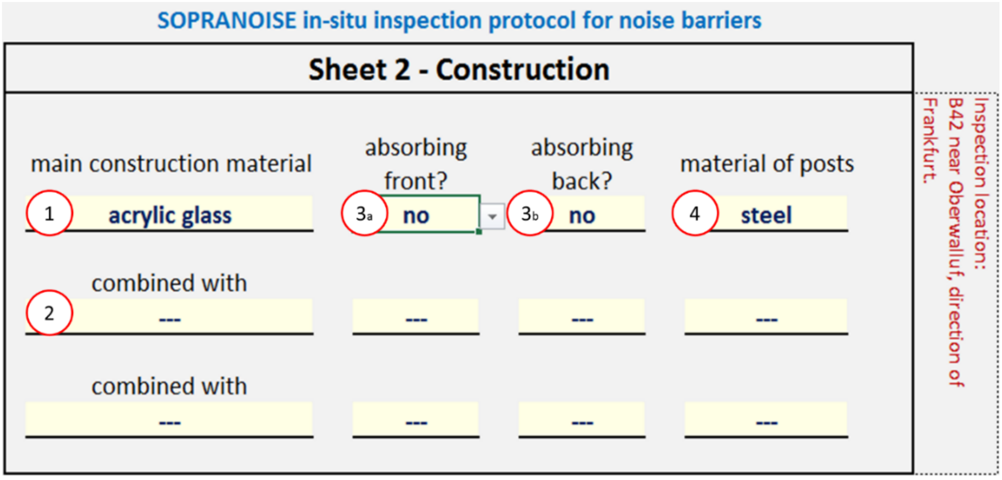

Figure 5: Screenshot of the second input sheet ‘Construction’ with exemplary entries

Step 3: Defects (inspection on site)

The main sheet of the in-situ inspection protocol and the one to be filled in on site during the inspection is the sheet ’Defects‘. The information protocolled here is mostly relevant for the acoustic assessment calculated on the next sheet. Each row in the table represents a defect that has been identified by the inspector. All information describing the position, size and type of damage can be entered on this sheet. The check boxes can be used to indicate how the damage looks like and presumably occurred. Exemplary entries in the third sheet ’Defects‘ are shown in Figure 6. The inputs in the different columns of the table are described below by referring to the first defect protocolled in the example of Figure 6 (first row of the list).

1. Column is “field no.” Please enter the number of the noise barrier field here. 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. Column is “NB side”. Here you have to enter the 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. Column is “field height /m”. The height of the entire noise barrier field is indicated here. 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. Column is “defect location”. Here the location of the defect at the noise barrier field has to be indicated. 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. Column is “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”. Please tick each match here, 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. Column is “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. Column is “position /m vertical”. In this field you have to enter the position of the centre of the defect in vertical direction in ranges of 0.5 m. You can 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 lower one.
   In the example, the defect is vertically located in the height range “**1.5 - 2.0**“ m.
8. Column is “position horizontal”. This field is only used to describe 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. Column is “size /cm vertical”. This column is to describe the medium vertical extension of the defect under investigation. Here you can 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 lower 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. Column is “size /cm horizontal”. This column is to describe the medium horizontal extension of the defect under investigation. Here you can also 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 lower 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. Column is “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.

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)
				☐	☐	☐	☐	☐	☐						
				☐	☐	☐	☐	☐	☐						
				☐	☐	☐	☐	☐	☐						
				☐	☐	☐	☐	☐	☐						
				☐	☐	☐	☐	☐	☐						
				☐	☐	☐	☐	☐	☐						
				☐	☐	☐	☐	☐	☐						

Inspection location: B42 near Oberwalluf, direction of Frankfurt.

Noise barrier material: acrylic glass with --- and

Figure 6: Screenshot of third input sheet ‘Defects’ with exemplary entries

Step 4: Acoustic assessment

After completing the entries described above, the fourth sheet ‘Acoustic assessment’ can be called up. Here, the acoustic consequences of the damage are shown by using two different measures: firstly, via a traffic light colour rating, and secondly with the indication of the so-called radius of influence. The colour scheme is divided into red, yellow and green. Green stands for a negligible 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 be carried out using the "Quick method".

Moreover, two types of assessment are available. The left table shows the effect of each defect considered individually. The table on the right shows the estimated total effect of all recorded defects in superposition. See Figure 7.

After filling in the sheets ‘Location’, ‘Construction’ and ‘Defects’, the fourth sheet ‘Acoustic assessment’ immediately shows an estimation of the degradation of the acoustic performance caused by the recorded damages. This sheet is a pure output sheet. No entries are necessary or possible here. The output is given on the left side for each noise barrier field considered on its own, and on the right side taking into account the mutual influence of neighbouring defects. For each field (identified via the field number entered during the inspection), it can be recognised by means of the colour rating whether the effect of the damage is still within the tolerable range (green and "G" for "good"), whether further more detailed examinations must take place with the quick method or full measurements according to the standards (yellow and "Q" for "questionable") or whether a direct repair must be initiated (red and "D" for "defective"). The third column indicates the estimated radius of influence of the damage. On the right side, the acoustic consequence of the damage is displayed, considering the mutual influence of nearby defects (superposition). In this superposition the defect size and the distance from one defect to the other are considered. This naturally results in much 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.

SOPRANOISE in-situ inspection protocol for noise barriers

Sheet 4 - Acoustic assessment

Inspection location: B42 near Oberwalluf, direction of Frankfurt.

Assessment for each NB field individually			Estimated overall assessment (superposition)		
field no.	acoustic condition	critical radius /m	field no.	acoustic condition	critical radius /m
35	G	5	35	G	5
57	G	9	57	G	9
83	Q	17	83	Q	33
84	G	8	84	Q	34
86	G	3	86	Q	32
87	G	9	87	Q	29
98	Q	17	98	Q	17
					0
					0
					0
					0

Figure 7: Screenshot of fourth sheet ‘Acoustic assessment’ with exemplary output results

Step 5: Settings (optional)

The fifth sheet is again an input sheet, but here only global values are entered. The pre-set values, deposited next to the actual table, are the settings for the standard case. Normally, no changes are made here. Changes can have a great effect on the acoustic assessment and are reserved for specialists. Therefore, the sheet is protected against accidental entries. This protection must first be removed before a change can be made. To do so, the user simply has to right-click the sheet tab and select “Unprotect Sheet” from the context menu. After changing the settings, it is important to re-activate the sheet protection.

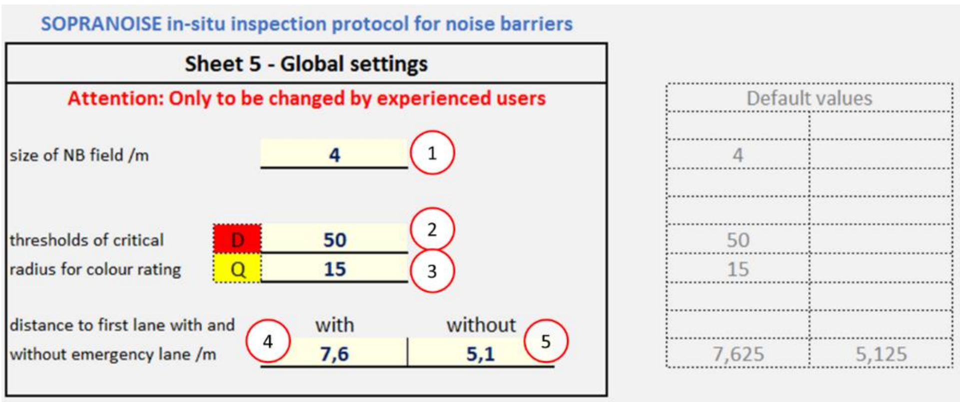

Figure 8: Screenshot of fifth sheet ‘Settings’ with default values

Exemplary entries in the sheet ‘Settings’ are shown in Figure 8.

1. Field is “size of NB field /m”.
   A common length of noise barrier elements used is 4 m. Changing this value does not change the acoustic assessment of the individual damages. However, it affects the calculated superposition on the right side of the output sheet. This is because a change in the field width defines the distances between two damages.
   The default value is 4 m and can be adjusted to the standard field length of the respective country.

2. Field is “thresholds of critical radius for colour rating / Defective”.
   This is the threshold value from **Questionable** to **Defective** condition. This value defines the "critical radius" at which a damage is considered to be so critical that the respective part of the noise barrier needs to be repaired from the acoustic point of view. The default value is 50 m and can be adjusted in the case of very close or very distant residential areas.

3. Field is “thresholds of critical radius for colour rating / Questionable”.
   This is the threshold value from **Good** to **Questionable**. This value defines up to which "critical radius" a damage is still considered acceptable from the acoustic point of view and no further measures are necessary. It may be useful to adjust this value for very close or very distant residential areas.
   The default value is 15 m and can be adjusted in the case of very close or very distant residential areas.

4. Field is “distance to first lane with emergency lane /m” and
5. Field is “distance to first lane without emergency lane /m”.
   This refers to the distance between the first lane and the noise barrier in the presence/absence of an emergency lane. It defines part of the geometry and thus the shielding effect of the noise barrier. The default values are 7.6 m and 5.1 m, respectively, and an adjustment may be necessary in the case of differing distances (see *short description* for details).

4 Conclusions

With the completion of Task 3.3, the WP 3 of the SOPRANOISE project is now finalised and the first stage of the progressive 3-step approach is fully developed. The result is a practice-oriented in-situ inspection procedure for the approximation of the degradation effect in the acoustic insertion loss of a noise barrier due to leaks. Its potential and features are summarised in the following list:

- **Simple and fast application:** The inspection procedure and calculations are realised as an easy-to-use *Excel* file, i.e. the inspection protocol. No additional tools are required. It can be filled in step-by-step on site and the inspector immediately can read off the result of the inspection.
- **Usable as add-on:** The in-situ inspection is designed in a way that it can be integrated into existing inspection procedures (regarding e.g. stability, road safety or durability), which are already in operation in the respective countries. It is supposed to work as an *add-on tool* to specifically address acoustic issues during an inspection.
- **Physics-based approach:** The calculations performed in the background of the in-situ inspection protocol are based on a well-functioning and validated theoretical model. An acoustic radius of influence is calculated based on the leak characteristics and geometrical parameters, leading to the acoustic rating of the inspection. The degree of approximation is chosen in a way that the procedure becomes applicable on site, but still yields relevant and meaningful information about the acoustic consequences.
- **Clearly defined scope:** No definitive decision can be taken on the basis of in-situ inspections only. Therefore, a scope is given which defines the range of application for the in-situ inspection (as well as for the other stages of the SOPRANOISE 3-step approach). The interpretation of the inspection results is also stated therein.
- **Documentation for users:** In order to put the in-situ inspection into practice, user-oriented descriptions must not be missing. Two descriptive documents are included to accompany the inspection protocol itself and provide all information necessary to carry out and understand the inspection procedure. The *manual* is a step-by-step instruction (including an example and screenshots) of how to fill in the inspection protocol, and the *short description* explains the theoretical background of the calculation and the functionality of the different parts of the protocol *Excel* file.

The focus of Task 3.3 was to improve and finalise the inspection procedure, to motivate and prepare its practical application, and to emphasize once more for which purposes it can and cannot be applied. It is now clearly stated that

- the in-situ inspection yields a first evaluation for the acoustic degradation of a noise barrier by estimating the impact of a defect on the insertion loss;
- the theoretical model is an approximation with several simplified assumptions, therefore the results have to be interpreted qualitatively;
- it is not possible to assess the acoustic consequences of a degradation in the sound absorption with the developed inspection protocol;
- an inspection method can never be used for the legal approval of a noise barrier, since it cannot replace quantitative acoustic measurements.

The acoustic in-situ inspection protocol is now ready to be used and already an extremely helpful tool to facilitate the systematic characterisation of noise barriers. Within the SOPRANOISE project, another practical testing will be carried out in parallel to the application of the quick measurement method in WP 4 – to make the connection between both steps and see how the inspection results can indicate the preferred locations for the application of the quick method.

Once the SOPRANOISE project concludes, the in-situ inspection will be submitted for standardisation. The underlying calculations and the implementation of the inspection protocol can be easily modified to meet new requirements: within the standardisation process, the method will surely advance and develop further, based on practical experiences from users and other demands raised by stakeholders.

5 References

[1] M. Chudalla, F. Strigari and W. Bartolomaeus, *SOPRANOISE report D3.1, Chapter T3.2 – Development and testing of methods based on in-situ inspection,* 2021.

[2] F. Strigari and W. Bartolomaeus, *SOPRANOISE report D2.2, Chapter T2.3 - Influence of acoustic degradation of noise barriers on the total noise reduction,* 2021.

[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.