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Virtual certification of acoustic performance for freight and passenger trains

D 1.9:
Transposition procedure for END noise sources

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EXECUTIVE SUMMARY

Assessment of noise mapping required by the European Noise Directive will be submitted to a dedicated harmonized methodology: the CNOSSOS methodology. For computing the noise mapping around the railway network, CNOSSOS requires input railway noise sources in a specific format: 2 equivalent point noise sources at 2 different heights that represent the total noise power radiated by the vehicle and the track during train pass-by. On the other hand, virtual testing of vehicle allows providing pass-by noise of a rolling stock for various conditions of running at different receiver locations.

This document describes how to take advantage of virtual testing for providing CNOSSOS input. It focuses particularly on traction noise and rolling noise. The proposed methodology is the following:

- First, the virtual vehicle that corresponds to the vehicle model within virtual testing has to be adapted to the requirement of CNOSSOS: the sources to be used should correspond to commercial running conditions.
- The virtual testing, as developed for certification purposes, is used to provide pass-by noise simulations i.e. the virtual vehicle is then implemented in a dedicated numerical tool.
- In parallel, the numerical tool used for vehicle pass-by simulation is also used for simulated CNOSSOS equivalent noise sources pass-by.
- These equivalent sources are finally fit to create the same pass-by noise than the virtual vehicle.

The 2 CNOSSOS equivalent sources are consequently defined. In comparison to a method only based on measurement data, this approach allows a more accurate allocation of source sound power between the 2 source heights: this will be particularly important for assessment of noise for track equipped with low noise barriers. Thus, virtual testing could be an efficient method for providing input for CNOSSOS requirements, with a high level of accuracy and reliability.

Apart from this methodology, the document also proposed analysis and first remarks about the equivalent source formats proposed in CNOSSOS.

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1. INTRODUCTION

The European Noise Directive (2002/49/EC) requires EU Member States to determine the exposure to environmental noise through strategic noise mapping and to elaborate action plans to reduce noise pollution.

In 2009, the EU commission decided to develop the CNOSSOS-EU tool (Common Noise aSSessment MethOdS) as a common approach for assessing noise levels in Europe. This tool is based on a common method for predicting the sound propagation in the environment so that noise levels can be assessed and noise mapping computed in a consistent way. This method can handle several types of noise source such as automotive, aircraft, industrial and railway noise sources.

For the railway part, the CNOSSOS method requires, for each line section considered, a description of each type of rolling stock running on this line and a description of the traffic on this specific line. The operators are responsible for providing input data describing the different noise sources characterizing the railway system. A specific process is defined for rolling noise: its equivalent noise source is computed within the CNOSSOS tool with input parameters such as wheel/rail roughness and wheel/track transfer functions. For the vehicle specific noise sources (called traction noise sources in CNOSSOS), the equivalent sources used for CNOSSOS input are currently defined with a dedicated post-processing of pass-by measurements. Additionally CNOSSOS-EU allows for aerodynamic sources, impact noise at crossings, switches and rail joints and curve squeal noise.

The ACOUTRAIN project is mainly concerned with the potential for introducing Virtual Testing within the framework of the acceptance of new vehicles. In the ACOUTRAIN project, the train is considered as a set of noise sources. To perform a numerical assessment of the train noise, all the sources have to be defined as noise sources with specific noise levels and directivity. The stationary and/or pass-by noise of the train can then be assessed in a dedicated tool (called numerical tool). Dedicated methodologies to define the different sources have been developed in ACOUTRAIN, as well as a specific format for the equivalent noise sources that acoustically defined the train and a numerical tool that can handle this input and provide train noise for stationary and pass-by conditions.

The present document proposes a methodology to use the process of virtual testing developed in ACOUTRAIN for defining the traction noise sources and the rolling noise source for the CNOSSOS approach. The second chapter of the present document presents the requirements concerning the input for the CNOSSOS approach. The third chapter presents the process that could be used for defining CNOSSOS input for the vehicle-specific noise sources (CNOSSOS equivalent noise sources of the traction noise sources) from a virtual vehicle defined in a virtual testing process as proposed in ACOUTRAIN. The fourth chapter addresses methods for obtaining input data for the rolling noise source.

2. EUROPEAN NOISE DIRECTIVE: CONTEXT AND REQUIREMENTS

Since June 2007, EU countries are obliged to produce strategic noise maps for all major roads, railways, airports and agglomerations, on a five-year basis. These noise maps are used by national authorities to identify priorities for action planning and by the European Commission to assess noise exposure across the EU. This information also serves to inform the general public about the levels of noise to which they are exposed, and about actions undertaken to reduce noise pollution to a level that is not harmful to public health and the environment.

A common approach for assessing noise levels in Europe is considered as a key prerequisite to have consistent and comparable figures on the number of people exposed to noise levels in and across EU Member States. To achieve this, Article 6.2 of the Directive foresees the development of a harmonised methodological framework for noise assessment. In 2009, the European Commission decided to develop CNOSSOS-EU (Common Noise aSSessment MethOdS) for noise mapping of road traffic, railway traffic, aircraft and industrial noise.

In 2012 the report [1] was produced that describes this harmonised mapping method.

As in any calculation method used for noise prediction, the CNOSSOS method requires a definition of the noise sources and a method to make them propagate in a given environment (with dedicated noise propagation methods). The noise source definition for railway noise is detailed in [1] and summarised in the following section.

2.1 Required source format for noise mapping according to CNOSSOS

The CNOSSOS method is a process proposed to define the strategic noise mapping. This process deals with the propagation of noise sources in complex environments.

The CNOSSOS method developed can be schematically represented by the two boxes in Figure 2.1:

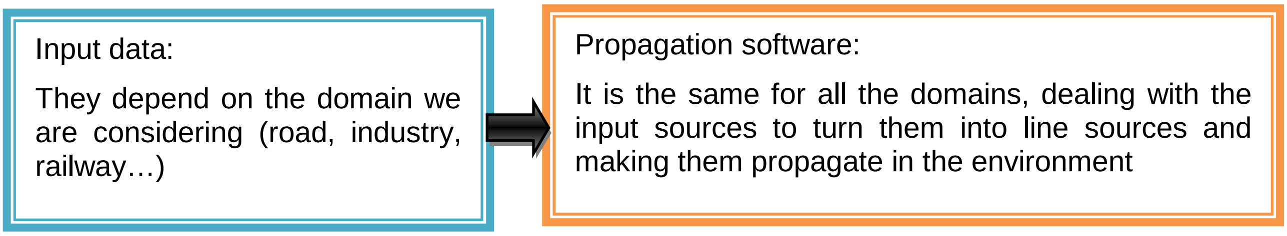

Figure 2-1: The two main steps in the CNOSSOS methodology

The first box concerns the input data definition: it is done depending on the type of infrastructure the user is dealing with. For railways, the input data are to be provided by the infrastructure manager from their own database and/or measurements. Reference input data can also be found in [1]. Although CNOSSOS works normally in octave bands, for railway noise sources the definitions are in one-third octave bands, with the results transformed to octave bands for use with the propagation models.

The second box deals with the propagation of noise in the environment, where real sources are described by a set of point sources or, in the case of railway traffic or road traffic by incoherent line sources. The CNOSSOS dedicated software will support a numerical model that simulates the propagation effect in a complex environment for various kinds of noise source.

It has to be noticed that the second box does not take into account pass-by effects for moving sources. It deals with diffraction (on surrounding buildings), ground effects and meteorological effects implied in the propagation effect. The pass-by effect should therefore be taken into account in the source input data.

According to [1], five kinds of sources are differentiated for the railway domain. This description is more complicated than is the case for other types of noise source. For example road vehicles are described by only two sources at one height and are defined by five vehicle categories. It has been decided that the train will be represented by two equivalent line sources at heights of 0.5 m and 4 m, each of them defined by an acoustic power and a directivity function:

1- Rolling noise, for which the equivalent line source is located at 0.5 m from the ground. A special case is made for the rolling noise: the equivalent noise source is directly computed in the CNOSSOS tool. It is done by using the following input data: total effective roughness (which can be obtained from wheel roughness, rail roughness and a contact filter), track transfer function and rolling stock transfer function.
2- Impact noise (crossings, switches…): the equivalent line source due to these kinds of noise sources is directly linked to the rolling noise by taking into account an additional 'roughness' (for the considered track section that contains the crossing and/or the switches)
3- Traction noise: equivalent line sources at two heights are considered, 0.5 m from the ground and 4 m from the ground. The report [1] gives recommendations concerning the characterisation of the physical traction noise sources, referring to the standstill measurement method described in ISO3095. However, no methodology is proposed for representatively characterizing motor and gearbox at standstill. Moreover, the different operation conditions applied for various cooling systems at standstill and running are not accounted for.
4- Aerodynamic noise: analytical equations are given in [1] to compute this noise source contribution (with equivalent line sources at two heights again). Some coefficients, determined from measurements, could complement the analytical model of aeroacoustic noise sources.
5- Squeal noise: this is associated with a source at 0.5 m from the ground. It should be applied for curves of radius less than 700 m. The noise emission should be specific to each type of rolling stock. However a simple approach is also mentioned in [1] in which the rolling noise level is increased by 8 dB for R<300 m and 5 dB for 300 m<R<500 m for all frequencies.

Considering the required noise source input for railway applications in the CNOSSOS method, it is clear that the equivalent traction noise source definition is under the responsibility of the infrastructure manager who may delegate the work to the railway operator that operates the considered rolling stock. While some examples are given in [1] of source spectra for rolling noise, only two examples are given for traction noise sources corresponding to an 'electric locomotive' and an 'electrically motored unit with gears'. The equivalent traction noise sources normally depend on the operating conditions of the train, which depends on the traffic related to the track section considered:

"Traction noise is generally specific to each characteristic operating condition: constant speed (including deceleration, when it is assumed to be the same noise as for constant speed), acceleration and idling. The source strength modelled here only corresponds to maximum load conditions. This results in the quantities $L_{W,0,const} = L_{W,0,dec} = L_{W,0,acc} = L_{W,0,idling}$ *(for constant speed, deceleration, acceleration and idling respectively). The appropriate one is to be used according to the operating condition of the train in each j-th track segment."* [1].

This method could be appropriate for diesel units but it is questionable for electrical units: indeed it is difficult to operate traction source at running conditions when vehicle is at standstill.

Until now, these sources are defined using standard pass-by measurements, as defined in ISO 3095: all the rolling stock operated by each railway operator should have been measured during pass-by and an inverse method allows the equivalent noise sources to be obtained.

"These quantities can either be obtained from measurements of all sources at each operating condition, or the partial sources can be characterised individually, determining their parameter dependency and relative strength. This may be done by means of measurements on a stationary vehicle, by varying shaft speeds of the traction equipment, following ISO 3095." [1].

These measurements are costly and potentially a very complex task, and there are virtually no databases of "rolling stock noise sources" currently available. Therefore, the present equivalent noise sources available for traction noise generally correspond to one operating condition, unlike what it is required in the CNOSSOS method:

"As far as relevant, several traction noise sources have to be characterised which might not be all directly depend on the train speed:
- Noise from the power train, such as diesel engines (including inlet, exhaust and engine block), gear transmission, electrical generators, mainly dependent on engine round per minute speed (rpm), and electrical sources such as converters, which may be mostly load-dependent;
- Noise from fans and cooling systems, depending on fan rpm; in some cases fans can be directly coupled to the driveline;
-Intermittent sources such as compressors, valves and others with a characteristic duration of operation and corresponding duty cycle correction for the noise emission.

As each of these sources can behave differently at each operating condition, the traction noise must be specified accordingly. The source strength is obtained from measurements under controlled conditions. In general, locomotives will tend to show more variation in loading as the number of vehicles hauled and thereby the power output can vary significantly, whereas fixed train formations such as electric motored units (EMUs), diesel motored units (DMUs) and high-speed trains have a better defined load.
There is no a priori attribution of the source sound power to the source heights, and this choice will depend on the specific noise and vehicle assessed." [1]

2.2 POTENTIAL FOR OBTAINING INPUT FOR CNOSSOS FROM ACOUTRAIN OUTPUTS

Within this context, the development of virtual vehicles in ACOUTRAIN, i.e. acoustic models of rolling stock for which all the noise sources forming the train are defined, for several operating conditions, is a good opportunity to help the definition of traction noise input data for the CNOSSOS process.

The major issue for using ACOUTRAIN virtual vehicles for defining CNOSSOS input is the transition from the certification context to the commercial running context. Typically, the track used for certification is a TSI-compliant track which could be non relevant for commercial running; and the operating conditions of vehicles used for certification tests could also be different to the ones used during commercial running. Indeed, the virtual vehicles are already built for acoustic certification purposes, with noise sources specifically defined in certification operating conditions. This does not correspond to the operating condition of the trains to be modelled in CNOSSOS, even if it is the same rolling stock, which must correspond to the "day-to-day", commercial running conditions of this rolling stock. Moreover, at certification the trains are in almost new condition (3000 km of running) whereas for environmental noise prediction the variation in condition over the lifetime of the rolling stock should be taken into account.

Regarding the other sources, the description of rolling noise within CNOSSOS is defined in a very specific way. Input data for the wheel roughness could be measured and the vehicle transfer function could be obtained from the virtual testing procedure (e.g. using TWINS models) if this is likely to differ from existing rolling stock. The transposition procedures for rolling noise developed in ACOUTRAIN, see [2], could also be used to provide this input data. Again the difference between new vehicles and the average behaviour over their lifetime needs to be accounted for.

Impact noise does not require any further input relating to the vehicles and the virtual testing process does not provide any input for this source.

Aerodynamic noise has been considered in WP3 of ACOUTRAIN but modelling is not considered mature enough to use virtual testing for this source group, see [3]. Nevertheless, it can be pointed out that the state-of-the-art of modelling implies that the speed dependence of this source should be at least 60 log V whereas the CNOSSOS model recommends that 50 log V should be used.

ACOUTRAIN has proposed a measurement protocol for curve squeal noise which could be used to provide input data for this source.

Chapters 3 and 4 consider the specific methodologies that can be proposed for traction noise sources and rolling noise. The characterization of the other sources is already well documented in the CNOSSOS document.

2.3 A NOTE ON DIRECTIVITIES

In the CNOSSOS report [1] sources are defined by a term called ‘directional sound power’. This is an unconventional usage as directivity is normally considered separately from the power. It essentially consists of a power and a directivity correction, so that the ‘directional power’ $L_{W,0,dir}$ is written as

$$L_{W,0,dir} = L_{W,0} + \Delta L_{W,dir,vert} + \Delta L_{W,dir,hor} \tag{1}$$

where $L_{W,0}$ is a sound power level describing the source and the remaining terms ΔL are directivity corrections (in dB).

The directivity terms are only introduced in the railway noise calculations. For automotive noise all sources assumed to be omnidirectional and for industrial noise no information is given about directivities.

For railway noise directivity functions are given in the CNOSSOS report [1]. The horizontal directivity is assumed *by default* to be a dipole

$$\Delta L_{W,dir,hor,i} = 10\log_{10}\left(0.01 + 0.99\sin^2(\phi)\right) \tag{2}$$

while the vertical directivities appear to be fixed. For source A the vertical directivity is given as the following frequency-dependent function:

$$\Delta L_{W,dir,vert,i} = \left(\frac{40}{3}\times\left[\frac{2}{3}\sin(2\psi) - \sin(\psi)\right]\times\log_{10}\left[\frac{f_{c,i}+600}{200}\right]\right)^{1} \tag{3}$$

This is always 0 dB at ψ=0, but increases slightly to values greater than 0 for ψ<45° with a maximum at 25° of 0.7 dB at 125 Hz increasing to 1.6 dB at 4000 Hz.

[1] In [1] modulus signs are included, making the correction always positive, but this is clearly incorrect and inconsistent with the figure given in the report. In addition eq. (3) seems not applicable for 90° <ψ<270° but it is unclear what should be used instead in this range may it needed for normalisation or for including ground effect.

For source B for aerodynamic noise the vertical directivity is 0 for ψ>0 and a horizontal dipole for ψ<0:

$$\Delta L_{W,dir,hor,i} = 10\log_{10}\left(\cos^2(\psi)\right) \tag{4}$$

It is omnidirectional for traction noise.

There is a problem with these directivity functions. Usually, directivity functions are defined such that the energy-average over a spherical surface is unity (or 0 dB). This is not the case for the functions defined in the CNOSSOS document [1]; they are mostly normalised to a maximum value of 0 dB (with the exception of the vertical directivity for source A). Consequently the power $L_{W,0}$ is not the total power of a source but the power of an equivalent monopole source that radiates the same pressure as the true source in the direction ψ=0, ϕ=π/2.

3. METHODOLOGY FOR CNOSSOS INPUT DATA DEFINITION FOR TRACTION NOISE SOURCE FROM A VIRTUAL VEHICLE DEFINED IN A VIRTUAL TESTING PROCESS

For a CNOSSOS calculation, the input needed to take into account the traction noise sources (also called in the ACOUTRAIN project vehicle-specific noise sources) are point sources, at heights of 0.5 m and 4 m, that represent the total acoustic power of all the noise source contributions on the rolling stock. Then, the definition of equivalent line sources that represent the contribution of the railway sources (traction noise + rolling noise + impact noise + aerodynamic noise if required) on a given track section is done within the CNOSSOS software from the different inputs.

Virtual testing as defined in ACOUTRAIN project requires a virtual vehicle that represents the train as a set of equivalent noise sources. This virtual vehicle is defined in a dedicated numerical tool. A specific tool has been developed within the ACOUTRAIN project, called ACOUTRAIN, and this tool will be considered in the following parts as the reference tool. However, several other numerical tools have been identified and assessed in the ACOUTRAIN project and could also be used for the process defined hereafter.

The inputs of these tools are the properties (sound power levels, directivities and locations) of the noise sources that acoustically define the train. According to the ACOUTRAIN process these noise sources can be defined with lab testing, with the source taken separate from the train. For these lab tests, representative operating conditions of the sources have to be used: the representative speeds for fans for example, or the representative load for converter and traction motor. Moreover, once these sources have been characterized in the lab in terms of sound powers and directivity patterns, it is required to assess the integration effects when they are mounted on the train. In fact, noise sources on train are very often roof mounted or under-frame mounted, with skirts or shields on their propagation path to the receiver. These effects are dominant on the noise radiated in the environment.

Once the sources and the integration effects have been assessed, the virtual vehicle (VV) of the train can be built. To verify that this VV correctly represents the real train in terms of noise emission, a dedicated validation procedure of VV has been proposed in the ACOUTRAIN project, based on comparison between simulation and real test results.

Therefore, this validated virtual vehicle represents very well the considered train in terms of its acoustic emission, in the frame of certification, i.e. for a train that has run 3000 km. To use for input to CNOSSOS three steps are proposed:

- to define the virtual vehicle with noise sources corresponding to commercial traffic
- to model the train in the ACOUTRAIN software without rolling noise
- to derive the source powers for input to CNOSSOS

3.1 Step 1: To define the virtual vehicle in ACOUTRAIN, with noise sources that correspond to rolling stock used for commercial traffic.

The virtual vehicle defined for certification purposes is composed of noise sources in a very specific condition: they should be representative of noise sources after around 3000 km of running, as required in the TSI. This specific condition could be no longer valid for noise mapping purposes: in that case, the noise sources should be representative of rolling stock in commercial use conditions.

For the vehicle-specific noise sources, that means values of sound power should be obtained from fans, motors, condensers, converters, etc after being used for thousands of kilometres. Alternatively, acoustic ageing laws in terms of acoustic performance should be defined for each component. This concept of ageing laws for vehicle specific components is a particular issue considering that one of the main reasons for changed source strength is mal-functioning or poor maintenance, e.g. clogging of filters: such effects cannot be modelled by ageing laws.

NB: in the following section, ageing of equipments is considered to have an impact on their acoustic performances. If some equipments are known to have constant acoustic performances over time (over kilometres of commercial running), then the assessment method described in the following section is no more required and the measurement of the equipment at certification conditions is sufficient for CNOSSOS use.

The data of representative noise sources for commercially used rolling stock should be given in terms of average values of noise levels representing the different states of the sources / the different ages of the sources for all the trains of the rolling stock fleet (for a given rolling stock fleet, all the trains are not the same age or state of maintenance). This is indicated in Figure 3.1.

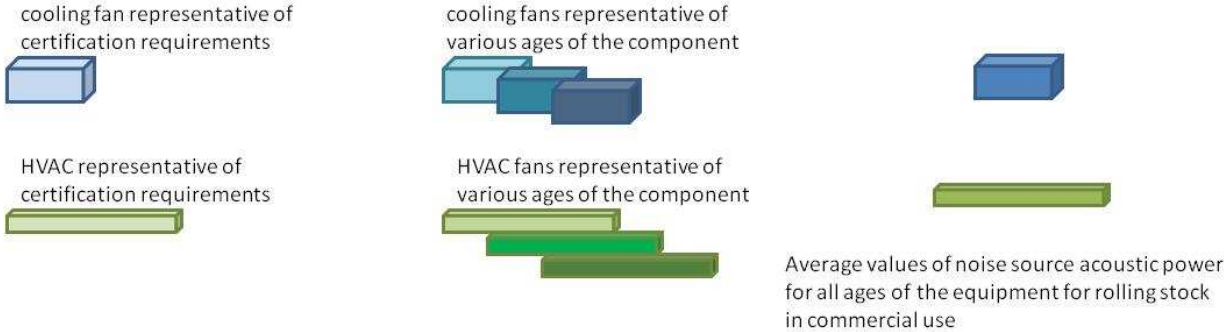

Figure 3-1: Noise sources from certification purposes to CNOSSOS purposes

Assessment of the average noise level for each source that corresponds to a rolling stock at different ages encountered in a commercial fleet is one of the major issues of the process proposed in this document. This assessment would mainly be based on measurements of the acoustic performance for a set of identical noise source at different ages (for example a given

HVAC or a given cooling system corresponding to the studied rolling stock). This requires the selection of a representative set of trains on which the source is mounted: they should correspond to the same rolling stock at different ages that could be encountered in the commercial fleet.

These measurements could not be carried out at the certification stage, as all the trains of the same fleet are new. In that case, assessment of average values for several ages of the different equipment would require pre-determined ageing laws, e.g. from existing rolling stock. It could also be proposed to postpone this assessment to a few months or years later: the trains would thereby be more representative of commercial running.

3.2 STEP 2: TO MODEL THE TRAIN IN ACOUTRAIN WITHOUT ROLLING NOISE

The first step allows a type of rolling stock to be defined as a set of noise sources, each of them being associated with a distribution of sound power that corresponds to the variability of sound power emitted by this source over its lifetime.

Once these sources are characterized, a corresponding virtual vehicle can be defined, see Figure 3.2.

As rolling noise source is specifically taken into account in the CNOSSOS process, the virtual vehicle to be used in ACOUTRAIN for defining the equivalent noise sources should not contain rolling noise sources but only traction noise sources (vehicle-specific noise sources).

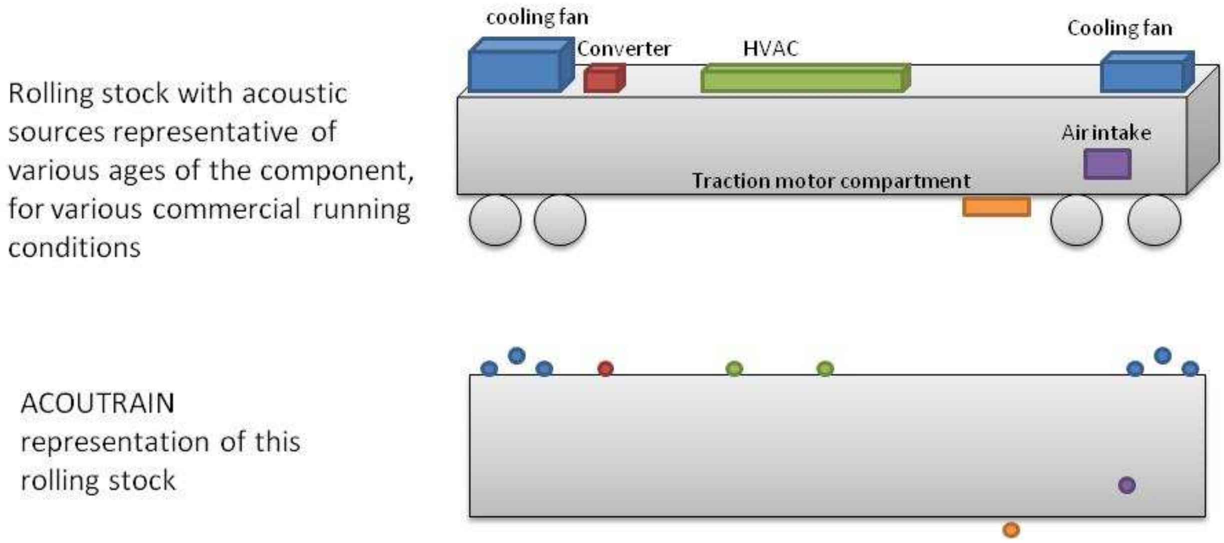

Figure 3-2: Rolling stock definition in ACOUTRAIN for CNOSSOS purposes

To define the equivalent noise sources, the same methodologies as proposed when defining the virtual vehicle for virtual certification purpose can be used:

- Equivalent monopole method to define equivalent set of monopoles as proposed in ACOUTRAIN deliverable 3.1 [5].

- Or other identification methods to define sources with a “power per face” representation.

The virtual vehicle is then defined, taking into account only the vehicle-specific sources (defined as traction noise sources in the CNOSSOS documentation). This vehicle is now ready to be used to provide the input needed by the CNOSSOS method.

3.3 STEP 3: TO DEFINE THE INPUT DATA FOR CNOSSOS FROM THE VIRTUAL VEHICLE OF ACOUTRAIN

For the CNOSSOS method, two equivalent point sources, at 0.5 m and 4 m height, have to be defined, that acoustically represent the vehicle-specific source contributions for the whole train. These equivalent noise sources are point sources that represent the contribution of the train pass-by on the considered track section (Figure 3-3). Two heights of sources have to be considered in CNOSSOS so that noise barriers impact could accurately be taken into account in the noise map implementation.

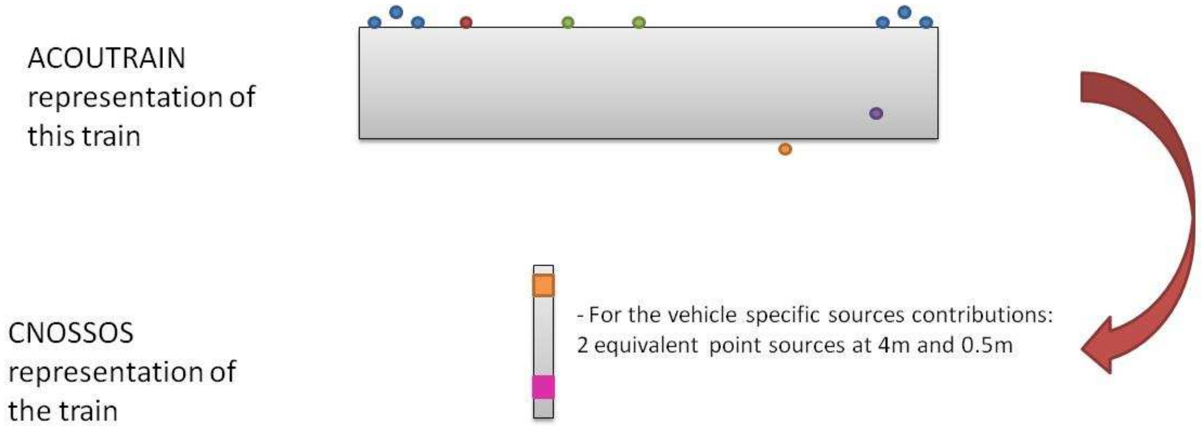

Figure 3-3: Noise source representation in ACOUTRAIN (distributed on the virtual vehicle) and in CNOSSOS

That means that the acoustic mean-square pressure “measured” at a given position (for example [7.5 m distance, 1.2 m height]) has to be the same if we consider the pass-by of the virtual train or the pass-by of the two CNOSSOS point sources. The distribution of the sources along the train is not taken into account as the evolution of sound level with time is not relevant in CNOSSOS; only time-averaged quantities (L_{eq}) are obtained.

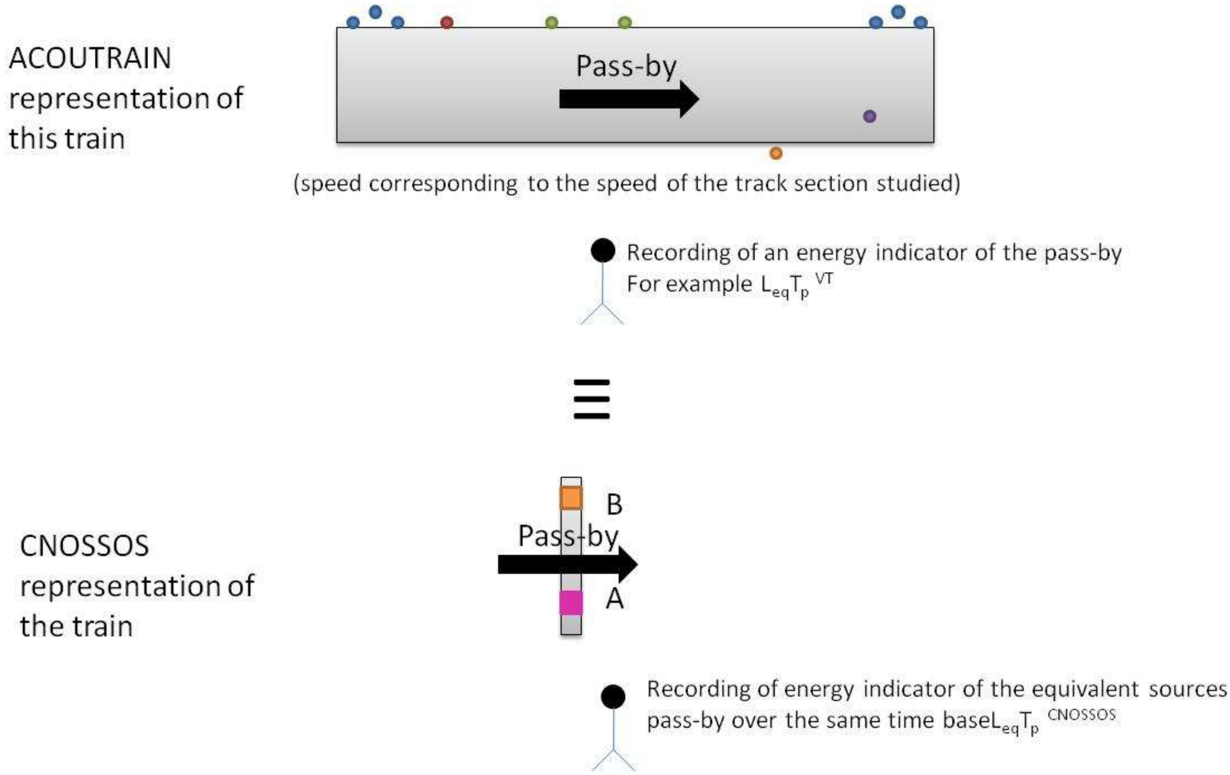

Figure 3-4: Principle of definition of CNOSSOS inputs from ACOUTRAIN simulation

Typically, the equivalent noise sources for the CNOSSOS representation *A* & *B* should ensure:

$$L_{eq,Tp}^{VT} = L_{eq,Tp}^{CNOSSOS} \quad (5)$$

for any microphone at any position, see Figure 3.4, where the time T_p should be the same in both cases.

The two unknown variables of this problem are the sound power of the two equivalent sources of the CNOSSOS representation: *A* & *B*. They are defined with a power spectrum level per one-third octave band and a directivity function.

Directivities are defined in CNOSSOS (see Section 2.3) and these values have to be used within this procedure. The two unknown variables are therefore: the acoustic power of source *A*, P_A, and the acoustic power of source *B*, P_B.

To assess P_A and P_B, an ACOUTRAIN calculation that simulates the pass-by noise of the considered rolling stock can be run for two times considering only sources below or above 2 m. This 2 m limit, which corresponds to the half of the height of source B, implies that most sources considered are either under frame or roof mounted making the results rather insensitive to the splitting plane location.
Each run will be used to estimate the sound power to be given at source A or B, respectively.

In particular the procedure can be summarised as follow.

1. Run the virtual vehicle calculations with only sources below 2 m activated to obtain the equivalent pass-by level at certain microphones M_i: $L_{eq,Tp}^{VT}(M_i)_A$.
2. For each microphone i, we will obtain $L_{eq,Tp}^{VT}(M_i)_A$. The equivalent source A for the CNOSSOS method has then to produce a $L_{eq,Tp}^{CNOSSOS}(M_i)_A$ which is equal to $L_{eq,Tp}^{VT}(M_i)_A$.
3. Considering simple propagation coefficients (free field propagation) that take into account the directivity of each source and pass-by effect (except Doppler effect) the following equation can be used to obtain the acoustic power of CNOSSOS source A, P_A.

$$L_{eq,Tp_{eq}}^{VT}(M_i)_A = L_{eq,Tp}^{CNOSSOS}(M_i)_A = 10log_{10}\left[\frac{1}{T_p}\int_{T_p}(x_i(t)P_A)dt\right] \quad (6)$$

$$10^{\frac{LeqTp^{VT}(M_i)_A}{10}} = P_A\frac{1}{T_p}\int_{T_p} x_i(t)dt \quad (7)$$

where $x_i(t)$ and $y_i(t)$ represent the pass-by effect of the sources: the equivalent source directivity coefficient (directivity pattern of the source seen by the receiver at each time step) and the propagation effect from the source to the receiver M_i, at each time step. They can be schematically written as:

$$x_i(t) = (D_v^A(t))^2\left(D_h^A(t)\right)^2\frac{1}{4\pi P_0\|M_i - M_A(t)\|^2} \quad (8)$$

$$y_i(t) = (D_v^B(t))^2\left(D_h^B(t)\right)^2\frac{1}{4\pi P_0\|M_i - M_B(t)\|^2} \quad (9)$$

P_0 is the reference acoustic power, $P_0=10^{-12}$ W

$\|M_i - M_A(t)\|^2$ is the varying distance at each time step between the microphone i and the source A.

$\|M_i - M_B(t)\|^2$ is the varying distance at each time step between the microphone i and the source B.

$D_v(t)$ and $D_h(t)$ are the directivity coefficients, for the vertical direction and the horizontal direction respectively, defined in the CNOSSOS report, see Section 2.3.

Not that eq. (7) results in a different value of acoustic power for different microphones position. Microphone at different heights can be used and the acoustic power P_A can be obtained by averaging the results.

4. The same procedure can be followed to obtain acoustic power of source B if only the sources above 2 m are activated in the virtual vehicle model.

To simplify the calculation of P_A and P_B, it is preferable not to take into account ground effect, neither in the ACOUTRAIN simulation (there is a possibility of doing pass-by simulation without any ground) nor in the expression of the propagation coefficients x_i^{Tp}, y_i^{Tp}. The ground effect will be taken into account in the CNOSSOS calculation for the noise mapping assessment but it is not needed for defining the sources.

4. METHODOLOGY FOR CNOSSOS INPUT DATA DEFINITION FOR ROLLING NOISE SOURCE

For the rolling noise the equivalent source is directly computed in the CNOSSOS tool. It is done by using the following input data: effective total roughness (made up of wheel roughness, rail roughness and contact filter), track transfer function and rolling stock transfer function.

The ACOUTRAIN project has contributed to defining procedures to obtain both the roughness and the transfer functions to be used in virtual vehicles. Although it is not strictly necessary for CNOSSOS users to adopt the techniques developed in ACOUTRAIN for rolling noise definition, it is appropriate to summarise here how these could be used to define CNOSSOS inputs. This may be convenient in particular when new vehicles have to be assessed and no information is available about the corresponding rolling noise transfer functions.

In particular, a standard procedure for wheel roughness measurements has been proposed in ACOUTRAIN Task 2.3 and reported in [10]. Guidelines on how to use TWINS to obtain track and vehicle transfer functions have been studied in Task 2.1 and the main recommendations are reported in [11]. Reference [12] is of particular interest in the context of defining transfer function for new vehicles; it details procedures for the prediction of rolling noise of vehicles equipped with wheels different than the standard monobloc-axisymmetric type. It is also possible to use transposition methods to derive transfer functions and/or roughness. Three methods to separate track noise and vehicle contribution from measurements have been studied in Task 2.4; these are described and compared in [2] where some example applications are also reported.

4.1 ROUGHNESS

Some examples of typical combined roughness are defined in the CNOSSOS report [1]. These are expressed, for each one-third octave wavelength band *i*, as the combination of rail roughness, wheel roughness and contact filter as

$$L_{R,TOT,i} = 10\log_{10}\left(10^{L_{r,TR,i}/10} + 10^{L_{r,VH,i}/10}\right) + A_{3,i} \qquad (10)$$

where $L_{r,TR,i}$ is the rail roughness (in dB re 1μm), $L_{r,VH,i}$ is the wheel roughness and $A_{3,i}$ is the contact filter. As the examples covered by the CNOSSOS report [1] may not be exhaustive of all the possible scenarios, it is important to have common criteria on how to define inputs.

Within the ACOUTRAIN project attention has been focused in particular on wheel roughness levels $L_{r,VH,i}$. Several outcomes are available and they can form an additional basis for CNOSSOS inputs. Rail roughness has not been addressed further as it is already well covered by the European Standard EN 15610:2009 ([13]).

A procedure for wheel roughness measurement and analysis has been proposed which follows the main ideas of the European Standard EN 15610:2009, used for rail roughness. It gives details on the data acquisition and post processing. In addition the measurement and analysis procedure has been tested by a measurement campaign performed by four different ACOUTRAIN partners (see [14]). The consortium cooperation has also resulted in a database from which wheel roughness can be derived depending on the braking system used, as also recommended in [1]. Some example results have been reported in [15].

In addition, characterisation of the contact filter effect ($A_{3,i}$) has been studied in Task 2.6 of ACOUTRAIN project. A summary is reported in Deliverable 2.7 ([16]) focusing in particular on an experimental characterisation of the contact filter. Together with the theoretical models available ([17]) this can provide the basis for estimating the term $A_{3,i}$ in eq. (10). Moreover, in making these comparisons it was discovered that the contact filter listed in [1] is not the most up-to-date estimate of the result from the DPRS filter.

4.2 TRANSFER FUNCTIONS

With regard to rolling noise transfer functions the CNOSSOS report states [1]:

> *"Two speed-independent transfer functions, $L_{H,tr,i}$ and $L_{H,veh,i}$ are defined for each j-th track section and each t-th vehicle type. They relate the total effective roughness level with the sound power of the track and the wheels respectively. These functions can be obtained from specific measurements but are also tabulated for some common cases in Appendix IV-B"*

Although the CNSOSS report includes some examples of track and vehicle transfer functions, it may be necessary to define new inputs. This is particularly important when new vehicles have to be included. The ACOUTRAIN project has studied the robustness of available methods for obtaining the vehicle and track noise contribution either by means of measurements and calculations.

One of the most common way of calculating sound power from track components (both rail and sleeper) and wheels is by means of TWINS. TWINS is a model for rolling noise developed in the 1990s on behalf of ERRI (now UIC) and implemented in software [18]. It has been subject to two validation measurement campaigns ([19], [20]) and it is currently adopted in many countries. With the aim of harmonising the usage of TWINS and the definition of input parameters, the ACOUTRAIN project has provided a "user guide" ([11]) describing best practice for modelling wheels and tracks. A set of benchmark calculations has been performed by four ACOUTRAIN project partners. The benchmark cases have been defined in terms of all the important parameters that are usually known. Specific recommendations are given about defining wheel and track parameters. The main output of TWINS consists in the track and wheel transfer functions that can be associated with the transfer functions, $L_{H,tr,i}$ *and* $L_{H,veh,i}$ required by CNOSSOS.

Normally TWINS is adopted to assess axisymmetric monobloc wheels. In order to overcome this limitation the ACOUTRAIN project has produced recommendations on how to model different types of wheel [12]. In particular the following wheel types are covered: (i) (weakly) non axi-symmetric wheels, (ii) wheels with braking discs, (iii) resilient wheels and (iv) wheels with dampers. It is envisaged that there might be the necessity of following the directions of this ACOUTRAIN report when it is required to assess environmental noise due to trains with these types of wheels.

In addition the ACOUTRAIN project has explored different ways of obtaining track and vehicle transfer functions by adopting separation and transposition techniques from pass-by measurements or from a combination of measurements and calculations. However it has been found that separating noise components from pass-by is not a simple task. Each of the methods presented in Deliverable 2.5 ([2]) should be used with care as none is guaranteed to produce reliable results. It is recognised that further research is needed to improve this type of technique.

The same procedure proposed in Section 3 for traction noise, can be followed to obtain the equivalent rolling noise source for CNOSSOS. The transfer functions possibly obtained in one of the ways outlined above can be simply adopted to calculate the sound power associated with rolling noise as explained in [1]. It is important to take correct account of the directivity functions proposed in [1] which are normalised differently from those used in TWINS.

5. HOW CNOSSOS BENEFITS FROM VIRTUAL TESTING?

The current process for assessing input for noise mapping assessment generally consists in measuring on a limited number of track sections, the different rolling stocks that have to be taken into account for the noise map of the considered network. The measurements are generally carried out according to ISO 3095 requirements: microphones at 7.5 m from the track, at one or two heights (1.2 m and potentially 3.5 m). From the measured global level, equivalent noise sources are then defined for each representative rolling stock to be used in noise maps calculation. The noise sources defined correspond to one vehicle on a specific track section (the one where measurements were performed).

The previous sections describe a methodology for assessing CNOSSOS input from virtual testing process as it has been designed for certification purposes.

Using virtual testing for CNOSSOS input definition presents several obvious advantages:

- The virtual approach will give reliable data: all the source models used within this approach would have been previously validated for certification purpose and would therefore present a high degree of confidence and accuracy.
- The allocation of sources sound power to the upper or lower equivalent source will be more accurate: this will allow a better estimation to be done when considering low noise barriers in the noise maps implementation.
- CNOSSOS input definition with virtual testing will be done at almost no cost: the virtual vehicles have to be set up anyway for the certification process. Only potential ageing laws have to be dedicatedly assessed.
- The virtual approach allows taking into account track and vehicle variation over time and space: it could then allows reliable studies to be carried out on the impact on environmental noise of regular track maintenance operations such as grinding or the impact of noise mitigation measures installed on track or vehicle such as rail dampers or wheel dampers.

Virtual testing could be an efficient method for providing input for CNOSSOS requirements, with a high level of accuracy and reliability.

6. CONCLUSION

CNOSSOS approach allows computing noise maps required by the European Noise Directive (2002/49/EC). Concerning the noise mapping linked to the railway network, the CNOSSOS approach requires the definition of the railway system noise sources and the traffic on the different lines that have to be taken into account.

Railway operators are therefore in charge of providing the traffic on each line and the noise sources for the different types of rolling stock running on the considered line.

Concerning the vehicle-specific noise sources, or traction noise sources, these are currently defined in CNOSSOS with specific post-processing of dedicated pass-by measurements. It is proposed to use what is done in the ACOUTRAIN virtual testing process to define the CNOSSOS equivalent noise sources from the virtual vehicle models built within the virtual testing process. A methodology has been specifically proposed so that:

- The noise sources used in the virtual vehicle are representative of commercial use of the rolling stock.

- And the equivalent noise sources for the CNOSSOS approach are easily derived from specific computations performed with a virtual vehicle.

The major challenge for using the proposed methodology is the characterization of noise sources that correspond to commercial use of the rolling stock. This will require measurements of the different noise sources at different operating conditions and at different ages of the rolling stock. Alternatively, “acoustic ageing laws” (evolutions of the acoustic performances over time) could be established for the different equipment (fans, traction motor, cooling systems, air conditioning systems, etc).

Concerning the rolling noise, its equivalent noise source can be assessed directly in the CNOSSOS tool, with input parameters such as rail/wheel roughness and track and wheel transfer functions. It has been shown that ACOUTRAIN project outcomes can contribute in defining rolling noise input either in terms of roughness and transfer functions: both the modelling guidelines using TWINS and the database for wheel roughness measurement should add considerable value to the CNOSSOS approach.

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