SP Technical Research Institute of Sweden

Tuning of the acoustic source model

Aiming at accurate noise assessments along high-speed railways

Xuetao Zhang

Sustainable Built Environment

SP Report 2015:42

Tuning of the acoustic source model

Aiming at accurate noise assessments along high-speed railways

Xuetao Zhang

SP Technical Research Institute of Sweden

SP Technical Research Institute of Sweden
Box 857, SE-501 15 Borås, Sweden (headquarters)

SP Report 2015:42
ISSN 0284-5172

Abstract

The former SP acoustic source model for noise assessments along high-speed railways has been tested and inspected. It is proved that in general the SP acoustic source model works quite well in the important frequency range when no noise barrier presented. However, the test calculation also showed a need for a further study on the pantograph noise emission data because this high-location noise source is the most concern for applying a proper noise measure along the Sweden's first high-speed line, the East Link.

The inspection made in Project 1 proposed to lower the pantograph noise emission data by 1.5 dB. In this project, Project 2, the report from Project 1 was taken as the input. After a systematic study on the issue, it was concluded that it is acceptable to reduce the pantograph noise emission data by 1.5 dB. Moreover, by referring to the representative European HST pass-by data provided by Project 1, the following revisions are made: (1) the noise emission data for rolling noise at 3150 Hz was reduced by 2.5 dB; (2) the bogie component of aerodynamic noise below 315 Hz is handled differently than higher frequencies because of the monopole feature; (3) rolling noise components above 5000 Hz are handled differently than lower frequency components. Furthermore, pantograph noise below 200 Hz was made free of resonance peaks. The tuned noise emission data has been worked out and provided in tabular values for each of the four partial sources (rail/track, wheel, aero-bogie and pantograph), for a frequency range from 25 Hz to 10000 Hz and a speed range from 30 km/h to 320 km/h.

Dispersions of the noise data for rolling noise, aerodynamic noise and pantograph noise were also investigated.

Key words: Acoustic Source Model, High-Speed Train Noise, Pantograph Noise, Noise Data Dispersion

Summarised conclusions

- In the report from Project 1 (Anders Frid, Rapport 6068065-01, 2015-07-03, ÅF Industry AB), following information can be read:

    1. pass-by noise data L_{AeqTp} of six representative European HSTs, typical barrier insertion loss of HST pass-by noise, a set of supplier's source contributions to L_{AeqTp} at 25m distance;
    2. the SP source model works quite well compared with the representative European HST data in the important frequency range, when no noise barrier presented;
    3. it is proposed to reduce the SP noise emission data for pantograph noise by 1.5 dB;
    4. some other useful information.

- In this project, Project 2, the report from Project 1 was taken as the input. A systematic investigation was made with the focus on pantograph noise emission data.
- After a systematic study on the issue, it was concluded that it is probable and then accepted to reduce the pantograph noise emission data by 1.5 dB. And, a further more reduction is considered too risky to be realistic.
- Moreover, the noise emission data for rolling noise at 3150 Hz was reduced by 2.5 dB by referring to the representative European high-speed train pass-by data provided in the report from Project 1.
- Low frequency components ($\leq$ 250 Hz) of the bogie-area aerodynamic noise should be handled differently than higher frequency components when using X2 noise data to work out a default HST noise data, because these low frequency components originate from a monopole source.
- The high frequency (> 5000 Hz) components of rolling noise should also be handled differently than lower frequency components, when using X2 noise data to work out a default HST noise data. The possible reasons are: the contact filter effect, the function frequency range of rail/wheel dampers, less effective (?) at short wavelength range of a rail grinding procedure, etc. However, at this moment, it is not certain to give an explanation.
- The tuned noise emission data have been worked out and provided in tabular values for each of the four partial sources (rail/track, wheel, aero-bogie and pantograph), for a frequency range from 25 Hz to 10000 Hz and a speed range from 30 km/h to 320 km/h.
- The calculation showed that this tuned acoustic source model works well in the whole frequency range also when noise barrier is presented.
- Dispersions of the noise data for rolling noise, aerodynamic noise and pantograph noise are investigated. Roughly speaking, these dispersions are about $\pm$1.5 ~ 2 dB.
- Possible further reduction in noise limit values in 2028 is briefly analysed. 1 dB is thought as a reasonable estimation.
- The tuned noise emission data do not need to be further adjusted if noise limit values will have been lowered by 1 dB.

Preface

This project, Project 2, is funded by the Swedish Transport Administration (Trafikverket), with a reference number TRV2015/70657.

The output from Project 1 (Anders Frid, Rapport 6068065-01, 2015-07-03, ÅF Industry AB) was taken as the input to this project. The noise data provided in that report, pass-by L_{AeqTp} data of six representative European high-speed trains, typical barrier insertion loss of high-speed train pass-by noise, a set of supplier's partial source contributions to L_{AeqTp} at 25m distance, as well as some other useful information, made it possible to tune the acoustic source model.

Kjell Strömmer (Trafikverket) promotes and arranges the Project 1 and Project 2.

All the above contributions are gratefully acknowledged.

Borås 2015-07-26, 1st draft
Göteborg 2015-08-02, 2nd draft
Göteborg 2015-08-28, 3rd draft

Xuetao Zhang

Contents

1 Introduction

The East Link (Ostlänken) will be constructed to be a new double-track high-speed railway in the eastern part of Central Sweden. It is Sweden's first high-speed line specifically adapted to trains for high speeds, up to 320 km/h. It could also be part of a future high-speed railway from Stockholm via Jönköping to Göteborg or to Malmö/ Copenhagen. The project is the largest investment in the national plan for the transport system for the period 2014-2025. The first trains are expected to be operational around year 2028.

Swedish Transport Administration (Trafikverket) demands to make noise assessments along the high-speed line, and then to define and establish noise protection measures where necessary. The Nordic sound propagation model Nord2000 [1-4] is chosen for noise calculation for trains at speeds over 250 km/h, as well as at other speeds when high accuracy and precision is required [5].

In the earlier projects ordered by Swedish Transport Administration SP has developed an acoustic source model specially for future high-speed trains in Sweden [6,7]. The default noise emission data was worked out based on X2 train source data (in order to have proper spectrum data) while the total sound power level has been adjusted by referring to the TSI noise requirements for high-speed rolling stock (HS RST TSI) [8] (in order to have a proper noise emission level). This set of noise emission data has been tested in the East Line project and the first noise calculations showed a big worry – the noise action would cost huge. Considering a X2 train can differ from a real high-speed train (HST), especially their pantographs can have different acoustic characteristics. As pantograph is located 5m above top of rail, its contribution to the total noise level is the most concern because (1) a 2m-high noise barrier, or, other noise measures, can be considered where necessary to reduce noise impact from those low-height sources but (2) for pantograph noise there is currently no simple noise measure available. Therefore, there is a need for a further study on the noise emission level of this noise type in order to properly plan a noise action.

From 1 January 2015, new test methods and new noise requirements started to apply for new train types, described in the Regulation (EU) No 1304/2014 on interoperability [9]. The Regulation entails some changes to permissible noise levels compared to the requirements of the Commission Decision on the interoperability of high speed trains (2008/232/EC). Permissible noise limits can be expected to be updated approximately every 5 years. Noise data which meet the adopted noise limits regarding 2028 will need to be developed. Accordingly, Swedish Transport Administration wishes a further improvement of the acoustic source model in order to have the noise emission data being, if possible, even closer to the real ones of future HSTs; in other words, to have an even better accuracy and precision in making noise calculations. For reaching this purpose, Swedish Transport Administration has ordered two additional projects [5]:

1. Project 1: Comparing the SP acoustic source model and noise emission data with other methods and noise measurements that train manufactures possess, which may lead to a more accurate noise emission model. If necessary, adjustments in the source model will be proposed. Future noise requirements shall also be taken into account. This project would be conducted by ÅF and finished by week 27 (5 July 2015). The report of Project 1 will be taken as the input to Project 2.
2. Project 2: Adapting the acoustic source model and noise emission data for each individual partial source to the prognosis of EU noise requirements 2028. The task consists of two parts: (1) Noise emission data for each partial source and (2)

estimation of uncertainties in the noise emission data for each partial source. Project 2 would be conducted by SP and the report should be ready by 26 July 2015.

The report from Project 1 does provide some useful noise data to Project 2, like pass-by noise data L_{AeqTp} of six representative European HSTs, typical barrier insertion loss of HST pass-by noise, a set of supplier's source contributions to L_{AeqTp} at 25m distance, as well as some other useful information [10]. In next chapter these inputs will be discussed.

In Chapter 3 the acoustic source model will be briefly described and the tuning of the noise emission data will be made step by step, by referring to the inputs from Project 1 as well as the discussions presented in Chapter 2.

In Chapter 4 noise data dispersion will be discussed, which describes the uncertainty. The report is ended by Chapter 5 in which conclusion remarks are provided.

2 The new input

The report from Project 1 [10] provides several types of data as well as analyses useful for tuning of the noise emission data. In the following these inputs will be discussed.

2.1 Pass-by noise spectrum data

Through informal sources six pass-by spectrum data of anonymous but representative European high-speed trains were provided, as shown in Fig. 2.1.

More interesting is that the SP acoustic source model [7] has been tested to calculate L_{AeqTp} at 25m/3.5m position. The comparison between the calculation and the pass-by spectrum data of the representative European HSTs, shown in Fig. 2.2, indicates that the SP acoustic source model works “quite well in the important part of the frequency scale”.(Note: - 2 dB adjustment shown in Fig.2.2 seems not necessary; this will be discussed in next section.)

The comparison may suggest a tuning of the source data for rolling noise at 3150 Hz. For the source data below 315 Hz and above 5000 Hz it will be discussed in next chapter.

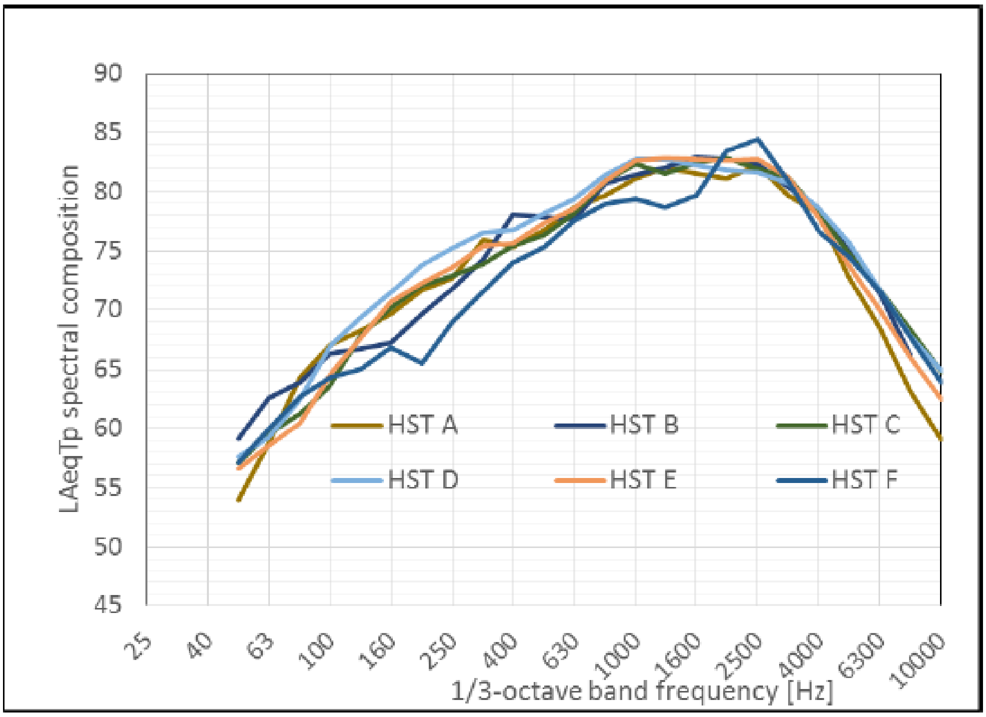


Fig. 2.1. *The pass-by spectrum data of six anonymous but representative European high-speed trains, at 320 km/h and measured at 25m/3.5m [10].*

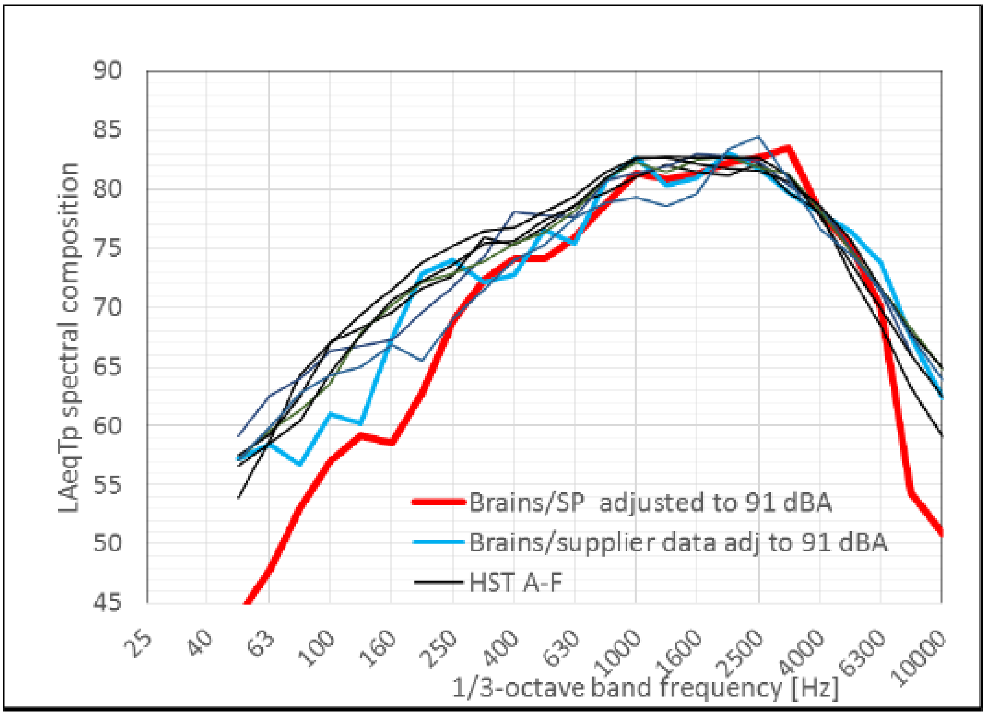


Fig.2.2. *Comparison between the calculations of L_{AeqTp} using the SP source data (adjusted -2 dB to get LAeqTp=91 dB) and the supplier's source data as well as the six representative European pass-by data at 25m/3.5m position [10].*

2.2 Partial source contributions to L_{AeqTp}

Table 11 in [10] (see Fig. 2.3 in the following) compared the partial source contributions to L_{AeqTp}, between the SP source data and the supplier's source data. This comparison suggests that the SP source data for pantograph noise can be reduced by 1.5 dB.

Source type	SP sources	Supplier source data
Rail	86.3	87.4
Wheel	88.9	82.5
Bogie aerodynamic	87.4	88.1
Pantograph	85.0	83.5
Total	93.2	92.0

Fig. 2.3. *Comparison of partial source contributions to L_{AeqTp} at 25m [10].*

Although not clearly described, the receiver height is likely to be 3.5m (above top of rail) and the train speed shall be 320 km/h. The author repeats the calculation using the SP source data and results are given in Table 2.1 and Fig. 2.4. Without 2 dB reduction the calculation shown in Fig. 2.4 fits the data the same well as that shown in Fig. 2.2.

However, the calculation results shown in Fig. 2.3 reflect the difference in the two sets of source data. It is possible to reduce pantograph noise by 1.5 dB, considering that the SP source data is not based on a real HST data while the supplier's source data must have some real HST data referred to.

As explained in [10], the wheels in the supplier's source data were equipped with noise absorbers, "which typically should be equivalent of 2-5 dB reduction on the wheel contribution".

The other difference is that, at 320 km/h, aerodynamic noise becomes more important than rolling noise in supplier's source data, while in the SP source data rolling noise is still the first important noise source. This is as understood due to the difference in noise measure of wheel damping.

Table 2.1. *Source contribution to at 25m/3.5m position, using the SP source data for 320 km/h. (The calculations were made by the author.)*

Source type	1m high track bed	3m high track bed
Rail	83,6	83,7
Wheel	87,2	86,6
Bogie aerodynamic	86,1	85,9
Pantograph	81,7	81,6
Total	91,1	90,9

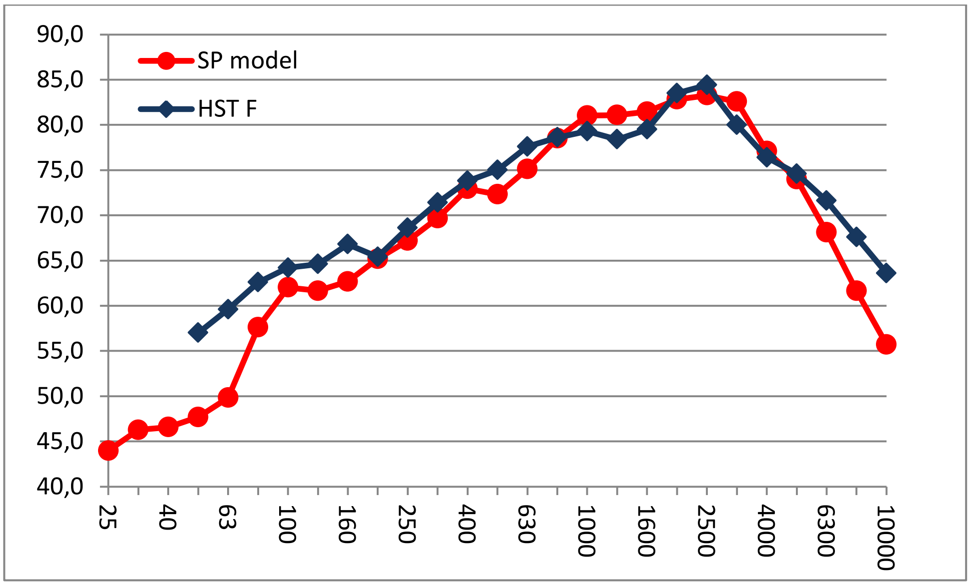


Fig. 2.4. *Similar as the calculation shown in Fig. 2.2, while the calculation was made by the author and the spectrum data of HST-F was estimated based on the curve shown in Fig. 2.1. The track bed height is 3m.*

2.3 Barrier insertion loss

The value of barrier insertion loss for a 2m high noise barrier is another useful reference in checking noise sound power distribution among partial sources. According to the information provided in [10], "Classified data from noise barrier test with high speed trains outside Sweden has shown that the insertion loss at 280 km/h is in the range 8-12 dB at the 25m position". (Note: receiver height shall be 3.5m above top of rail.)

Calculations presented in section 5 in [10] showed that, if SP source data for pantograph noise is reduced by 1.4 dB the barrier insertion loss (IL) will be 8 dB; and, IL will be 10 dB if 4.0 dB reduction is applied.

Calculations of barrier insertion loss have also been repeated by the author. Using the SP source data, for a 2m high noise barrier located 5m from the track centre, IL will be 8.8 dB if 1m track-bed height is used and 8.6 dB if 3m track-bed height is used (for a train pass-by speed 280 km/h). If SP source data for pantograph noise is reduced by 1.5 dB (while the total level of aerodynamic noise kept as a constant) IL will be 9.5 dB for a track bed of 3m height.

It is also interesting to look at the example shown in [20], presented in Fig. 4.1 and Fig. 4.2 in this report. In that example, the IL of a 2m high noise barrier at 280 km/h is about 10.5 dB.

Put the discussions in Sections 2 and 3 together, it seems acceptable to reduce SP source data for pantograph noise by 1.5 dB.

Note: The relevant calculation made in [10] seems contain a small error: the noise sound power for pantograph noise at 280 km/h was estimated from its sound power at 320 km/h by applying $50*\log_{10}$ (280/320). This is not correct; it should be estimated by applying $71*\log_{10}$ (280/320) (see Sub-section 3.2.3). In the speed range it is for the total sound power level the speed index of 5 is proposed to apply [9]. Consequently, this error leads to that the pantograph contribution is over estimated and then the barrier IL is under estimated.

2.4 The TSI noise legislation

According to Commission Regulation (EU) 1304/2014 of 26 November 2014, the newly updated version of NOI TSI (Technical Specifications for Interoperability) [9] is to apply from 1 January 2015. This new version of noise TSI integrates the noise requirements for high-speed rolling stock (HS RST TSI) into the previously existing CR NOI TSI which is for conventional rolling stock, also includes the revised requirements in the “transversal” TSI relating to Rolling Stock – Noise. One important merging is that the measurement position is now 7.5m from the centre of the track and 1.2m above top of rail for *all types of trains*, providing one additional measurement height of 3.5m above top of rail for high speeds (higher than or equal to 250 km/h). The limit noise values for pass-by A-weighted equivalent continuous sound pressure level are specified for at a speed of 80 km/h also, if applicable, at 250 km/h, for the defined vehicle categories.

Thus, for pass-by noise, there are three checking points for high-speed EMUs:

1. $L_{pAeq,Tp,(80\ km/h)}$ at 7.5m/1.2m position
2. $L_{pAeq,Tp,(250\ km/h)}$ at 7.5m/1.2m position
3. $L_{pAeq,Tp,(250\ km/h)}$ at 7.5m/3.5m position

In this updated version of NOI TSI noise limit values are reduced from 1 up to 5 dB [11]. As can be foreseen, noise limit values would be further reduced in 2028 by some extent, depending on technical development in train-track design as well as in noise mitigation. Referring to the information conveyed in [10], noise limit values are being revised regularly (so far it has been at 5-6 years intervals). “In a way, the approach is that the ‘best in class’ rolling stock at a certain time will serve as a target for limit setting a few years ahead. This way it is ensured that the limit values follow the technical progress.”

3 Tuning of the noise emission data

Based on the discussions made in Chapter 2, in this chapter the SP acoustic source model will briefly be described and the noise emission data will be tuned accordingly.

3.1 Rolling noise

Rolling noise has two partial sources, rail/track radiation and wheel radiation. The source heights are 0.01m and 0.5m above top of rail, respectively.

3.1.1 Directivity

The proposed directivity functions are listed below [7]:

The horizontal directivities for rolling noise are:

$$\Delta L_{\text{wheel}}(\varphi) = 10\lg[0.4 + 0.6 * \cos(\varphi)] - 20\lg[1 - M * \sin(\varphi)] \qquad (3\text{-}1)$$

$$\Delta L_{\text{rail}}(\varphi) = 10\lg[0.001 + 0.999 * \cos^2(\varphi)] - 20\lg[1 - M * \sin(\varphi)],\ f \geq 400\,\text{Hz}$$

$$\Delta L_{\text{track}}(\varphi) = -20\lg[1 - M * \sin(\varphi)],\ f < 400\,\text{Hz} \qquad (3\text{-}2)$$

where $M = v/c$ is the Mach number, v is the train speed, c the speed of sound in air; lg denotes for $\log_{10}$. The angles are defined in Fig. 3.1.

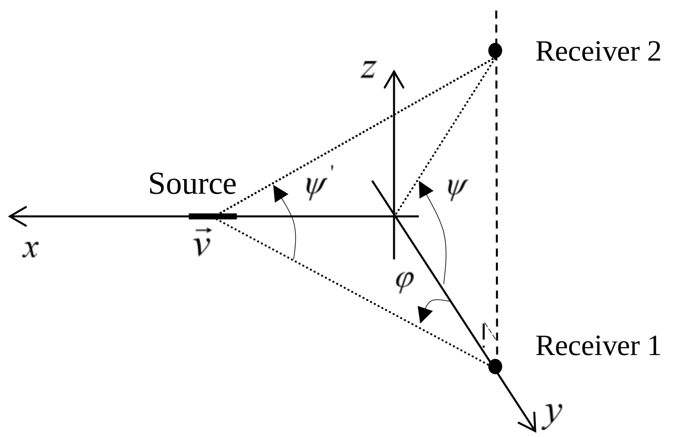


Figure 3.1. *Definition of angles: φ is a horizontal angle in the x-y plane and relative to the y-z plane; ψ is a vertical angle in the y-z plane; ψ' is a vertical angle in a vertical plane containing the receiver and the source (or the centre of the source line); both ψ and ψ' are relative to the x-y plane.*

The vertical directivities of wheel and rail noise can be described as $\Delta L(\psi) = 10\lg[0.4 + 0.6 * \cos(\psi)]$. However, the vertical directivity of total rolling noise depends also on the shielding effect of the train body and/or wheel skirts, as well as the near track noise barriers where they present. As these shielding effect varies with train type (and even with track section where near-track noise barriers present), a general vertical directivity function for total rolling noise was not specified because of lack of such data.

In the CONOSSOS-EU method [12], a vertical directivity function was proposed for total rolling noise

$$\Delta L_{vertical}^{R}(\psi) = \frac{40}{3} * \left[\frac{2}{3}\sin(2\psi) - \sin(\psi) \right] * \lg\left(\frac{f + 600}{200} \right). \qquad (3\text{-}3)$$

3.1.2 The indirect roughness method

The indirect roughness method was developed during the European project **MetaRail** (Methodologies and Actions for Rail Noise and Vibration Control) [13] and validated during the European project **STAIRRS** (Strategies and Tools to Assess and Implement noise Reducing measures for Railway Systems) [14]. Briefly, the indirect roughness method separates pass-by sound pressure spectra (not power spectra) into *total effective roughness* of the wheels and the rail and *total transfer function* of the vehicle and the track. (Note: By "effective roughness" means the rail roughness plus the wheel roughness plus the effect of the contact filter.) The total *effective* roughness (in wave-length domain) and total transfer function (in frequency domain) are given as $1/3$ octave band spectra. The separation is accurate within ± 3 dB per $1/3$ octave band. Combination of the total effective roughness, the total transfer function and the axles per meter gives an estimation of the pass-by sound pressure spectra, which is accurate within ± 1 dB(A).

The total effective roughness is derived from the vertical rail vibration measured during a pass-by. The total vibro-acoustic transfer function is determined using the derived total effective roughness and the measured sound pressure from the pass-by.

The basic measurement setup is shown in Fig.3.2.

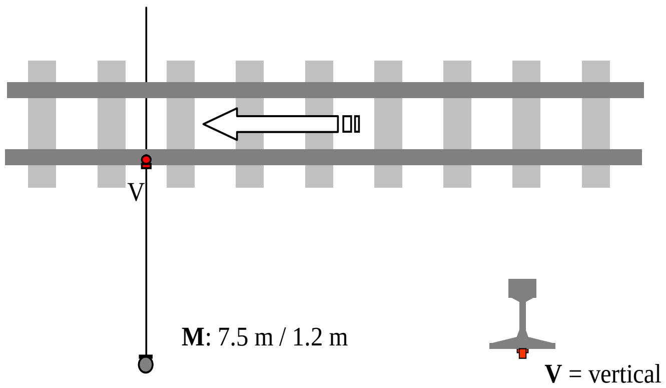


Fig. 3.2. *The measurement setup for collecting the time history data of rail vertical vibration and noise emission during a train pass-by.*

One extra accelerometer is proposed to use: it should be located about 30~50 m away from the first accelerometer and be used also for measuring rail vertical vibration. The advantage by using this second accelerometer is: (1) train speeds can be determined based on the recordings on the two accelerometers; (2) it becomes possible to improve the accuracy of the determined track decay rate by averaging over the data collected at two positions; (3) the effective total roughness will be determined not only by averaging over many wheels' roughness but also by averaging over the rail roughness at two positions.

The reason for the proposed distance shift, 30~50 m, is of two aspects: (1) a longer distance shift may be difficult to arrange and (2) the maximum cable length is technically limited according to the instrument specifications. (For example, when using 01dB measurement system together with ICP-accelerometer the maximum cable length is 85 m for covering one-third octave band 5 kHz, or, 42 m if covering 10 kHz [15].)

For collecting source data with good accuracy, it is required that, to avoid interference from accompanying wheel types, recordings containing at least two adjacent vehicles of the same type should be used to characterise a vehicle type, see Fig. 3.3. Such a time history recording of the rail acceleration levels is shown in Fig. 3.4. The average acceleration level and the equivalent SPL over the time interval T_p will be determined for each vehicle type as well as for each train pass-by.

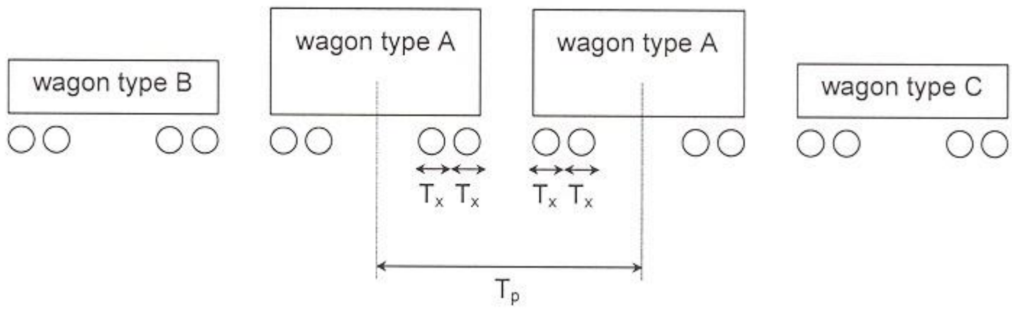


Fig. 3.3. *To measure vehicle type A, at least two wagons are required.*

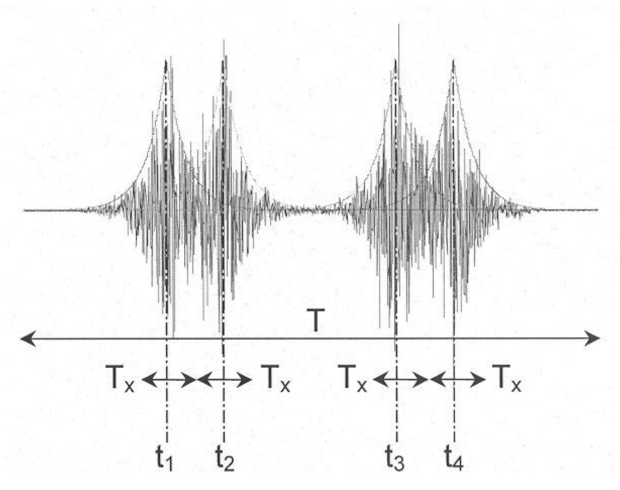


Fig. 3.4. *Vertical acceleration recording during four wheel passages.*

Two types of quantities are recorded:

- Microphone recordings of time history data of sound pressure level during a train pass-by (in short, the mic-data);
- Accelerometer recordings of time history data of rail vertical vibration level during the train pass-by (in short, the acc-data).

Three types of quantities are determined:

- The vertical track decay rate, using the acc-data;
- The effective total roughness, using the acc-data and the vertical track decay rate;
- The total transfer function, using the mic-data and the effective total roughness.

When rolling noise dominates in railway noise (usually true for a train speed between 50 km/h and 200 km/h), the total equivalent sound pressure level $L_{p,tot}$ during a train pass-by can be determined by

$$L_{p,tot}(f) = 10\lg\left(\frac{N_{axle}}{L_{wagon}}\right) + L_{H,tot}(f) + L_{r,tot}\left(\frac{v}{f}\right) \quad (3\text{-}4)$$

where

$L_{p,tot}(f)$	the equivalent total sound pressure level (for a specified pass-by time period) that is due to rolling noise and in 1/3 octave band
$L_{H,tot}(f)$	$L_{H,tot}(f) = L_{H,veh}(f) \oplus L_{H,tr}(f)$, the total transfer function in 1/3 octave band
$L_{r,tot}(v/f)$	$L_{r,tot}(v/f) = L_{r,w}(v/f) \oplus L_{r,r}(v/f) + CF$, the total roughness level in 1/3 octave band
$L_{H,veh}(f)$	vehicle transfer function, 1 axle per meter
$L_{H,tr}(f)$	track transfer function, 1 axle per meter
$L_{r,w}(v/f)$	wheel roughness level
$L_{r,r}(v/f)$	rail roughness level
CF	the contact filter
N_{axle}	number of axles per wagon
L_{wagon}	wagon length
f	$1/3$ octave band centre frequencies
v	train speed (m/s)

The key part of the method is to determine the total effective roughness. This quantity is to be determined as

$$L_{r,tot}(f) = L_{a,meas}(f) - A_1(f) - A_2(f) - A_4(f) - 40\lg(2\pi f) \quad (3\text{-}5)$$

where

$L_{a,meas}(f)$ 1/3 octave band level of equivalent vertical rail acceleration

$A_1(f)$ the level difference between the average vibration at the measurement point and the railhead:

$$A_1(f) = L_{a,meas}(f) - L_{a,head}(f) \tag{3-6}$$

Often one can take $A_1(f) \approx 0$.

$A_2(f)$ the level difference between the vibration displacement at the contact point on the railhead and the combined effective roughness:

$$A_2(f) = L_{x,contact}(f) - L_{r,tot}(f) \tag{3-7}$$

It describes to which extent roughness induces rail vibration. According to [16],

$$A_2 = 20\lg\left(\frac{|\alpha_R|}{|\alpha_R + \alpha_W + \alpha_C|}\right) \tag{3-8}$$

where

α_R rail receptance

α_W wheel receptance

α_C receptance of the contact stiffness

The spectrum A_2 is determined for a range of parameter values using the TWINS software [17]. *The pad stiffness is shown to be the most influential parameter*. In the frequency range from 100 to 3150 Hz inclusive, the spectrum A_2 can be determined to an accuracy of $\pm$ 3 dB for application to conventional wheels (given in Table 3.1), provided that the rail pad stiffness can be allocated to one of the three categories, as listed in Table 3.2.

$A_4(f)$ the level difference between the vibration at the contact point and the vibration of the railhead averaged over the wheel passage interval

$$A_4(f) = L_{a,head}(f) - L_{a,contact}(f) \tag{3-9}$$

$40\lg(2\pi f)$ = $L_{a,contact}(f) - L_{x,contact}(f)$, to convert from acceleration to displacement

The conversion spectrum A_4 depends on the spatial vibration decay *D* of the track [13]:

$$A_4(f) = L_{a,head}(f) - L_{a,contact}(f) = 10\lg\left\{\frac{8,686}{vDT_x}\left[1 - e^{\left(-\frac{vDT_x}{8,686}\right)}\right]\right\} \quad (3\text{-}10)$$

where v is the train speed and T_x the time length for the measurement illustrated in Fig. 3.4. The frequency dependent decay per meter, *D(f)*, depends on the track characteristics (mainly the rail pads). As the stiffness and damping of the rubber rail pad depends on lifetime, temperature, pre-load and the loading history, this quantity varies during the track lifetime, and even can vary during a train passage.

The spatial vibration decay of the track, *D(f)*, which is used in determining the conversion spectra of A_2 and A_4, can be measured according to the standard method shown in [18], or using a simplified method proposed in [19].

Table 3.1. *Spectra* A_2 *for three categories of rail pad stiffness [14]*

Frequency (Hz)	Soft pad	Medium pad	Stiff pad
63	1.0	−3.0	−3.0
80	4.1	2.3	2.3
100	2.7	2.6	2.6
125	0.9	0.8	0.8
160	0.1	0.0	0.0
200	0.0	0.0	0.0
250	−0.6	0.0	0.2
315	−1.2	−2.6	−0.1
400	−1.3	−3.9	−2.8
500	−0.9	−4.8	−6.5
630	−0.9	−3.2	−8.1
800	−1.6	−2.6	−6.9
1000	−2.7	−4.3	−5.0
1250	−5.6	−6.2	−4.4
1600	−8.0	−7.5	−6.4
2000	−9.5	−8.8	−8.4
2500	−10.0	−9.8	−9.5
3150	−11.3	−11.2	−11.1
4000	−13.7	−13.6	−13.6
5000	−14.9	−14.8	−14.8

Table 3.2. *Proposed ranges of pad stiffness*

	Soft pad	**Medium pad**	**Stiff pad**
Biblock sleepers	≤ 400 MN/m	400 – 800 MN/m	≥ 800 MN/m
Monoblock sleepers	≤ 800 MN/m	≥ 800 MN/m	-
Wooden sleepers	all	-	-

3.1.3 Track and vehicle transfer functions

The indirect roughness method determines only the total roughness and the total transfer function. To further determine the rail and wheels' contributions to rolling noise one needs to separate the total transfer function into the respective track and vehicle transfer functions.

The ideal way to make this separation is to use a measurement vehicle with small wheels, around 650 mm in diameter or smaller. By using such a vehicle and moving it at a speed within 50 ~ 100 km/h, the wheels' contribution to rolling noise will be negligible compared with the rail/track noise. Thus, the track transfer function can, with a good accuracy, be determined as,

$$L_{H,tr}(f) \approx L_{H,tot}(f) = L_{H,veh}(f) \oplus L_{H,tr}(f), \qquad L_{H,veh}(f) << L_{H,tr}(f) \tag{3-11}$$

Whence the track transfer function has been determined, the vehicle transfer function for each train type can be determined straightforwardly, as the total transfer function can be determined accurately by measuring pass-by noise on the same track using the indirect roughness method.

However, it is often the case such a measurement vehicle with small wheels cannot be arranged. Thus, one has to use default track transfer function as a reference to estimate the real track transfer function. In the Harmonoise source model, such default transfer functions are provided. By trial-and-error, useful track transfer functions can be obtained by referring to these default transfer functions as exampled in the exercise made in [6].

In ref. [7] the track and vehicle transfer functions determined in [6] have been adjusted by referring to the CNOSSOS-EU proposal [12], in the way: from 500 Hz and above the same level difference between the track and vehicle transfer functions has been taken. The consideration behind this treatment is that from 500 Hz rail is usually decoupled from the sleepers; thus, the track and vehicle transfer functions depend only the geometrical parameters of the rail and wheels, provided no noise measure has been applied.

3.1.4 Tuning of the noise emission data

X2 train is found too noisy. Therefore, for rolling noise, the source data for a default HST is made based on X2 train source data while reduced by 8 dB [7].

As discussed in section 2.1, by comparing with the European representative HST data, the SP noise emission data for rolling noise seems need a small adjustment around 3150 Hz. After reducing 2.5 dB, the abnormal protruding in spectrum at this frequency is deleted.

Fig. 2.2 also shows a big difference between the prediction using the SP source data and the representative European HST data, above 5000 Hz. It is known that rolling noise dominates at these high frequencies. As the SP source data works well in predicting X2 train noise [6], then the question becomes that if these high frequency components of rolling noise should NOT be reduced by 8 dB when shifting from a X2 train to a HST? There are some arguments against this reduction: (1) The contact filter effect implies that a change in roughness level at very short wavelengths is much less effective than at long wavelengths. (2) Rail dampers usually work below 1600 Hz; and, wheel dampers are usually tuned around 2500 Hz; these dampers are less effective above 5000 Hz. (3) Acoustic rail grinding may not be effective at short wavelengths. Although at this time it is not certain to give an explanation for this high-frequency behaviour, it is decided to follow the information conveyed by the European representative HST pass-by data and to tune the rolling noise emission data, in the way: - 8 dB for $f \leq 5000$ Hz, - 0 for $f = 10\ 000$ Hz, and a smooth transition in the between.

The noise emission data for rolling noise will not be further revised below 315 Hz because at such low frequencies aerodynamic noise dominates.

3.2 Aerodynamic noise

Aerodynamic noise has been assigned two source heights in the SP source model: 0.5m and 5m above top of rail for bogie components and pantograph noise, respectively.

In fact the other roof components of aerodynamic noise also contribute while not comparable to pantograph noise. And, the bogie components of aerodynamic noise may include the equipment noise (i.e. cooling fan noise) which could be the same important as other bogie component.

3.2.1 Directivity

The horizontal directivities for aerodynamic noise are proposed as:

$$\Delta L^{A}_{\text{pantograph}}(\varphi) = 10 * \lg\left[0.006 + (1-0.006) * \cos^2(\varphi)\right] - 40 * \lg\left[1 - M * \sin(\varphi)\right] \quad (3\text{-}12)$$

$$\Delta L^{A}_{\text{bogie}}(\varphi) = 10 * \lg\left[0.03 + 0.97 * \cos^2(\pi/2 - \varphi)\right] - 40 * \lg\left[1 - M * \sin(\varphi)\right] \quad (3\text{-}13)$$

However, for low frequency components (estimated $f \leq 250$ Hz), there is

$$\Delta L^{A}_{\text{bogie}}(\varphi, f \leq 250 Hz) = -40 * \lg\left[1 - M * \sin(\varphi)\right] \quad (3\text{-}13')$$

The vertical directivities for aerodynamic noise are proposed as:

$$\Delta L^{pantograph}_{vertical}(\psi) = 10 \lg[0.4 + 0.6 * \cos(\psi - \pi/2)] \quad (3\text{-}14)$$

$$\Delta L^{bogie}_{vertical}(\psi) = 0 \quad (3\text{-}15)$$

3.2.2 To determine aerodynamic noise

"Aerodynamic noise is … very difficult to calculate despite large efforts over the years even if there are signs of improvements today" [10]. As theoretical modelling of railway aerodynamic noise is still limited to a few simple configurations [20], this noise type has been handled using an empirical method proposed in [6, 21]. Briefly, one should first measure train pass-by noise at a typical high speed ($v_0 \geq 250$ km/h). As the rolling component of the pass-by noise can be accurately predicted using the theoretical model TWINS [17], or the engineering method "the indirect roughness method" which was described in Sub-section 3.1.2, the contribution of the aerodynamic noise at this typical speed can be obtained by subtracting the rolling noise contribution from the measured total. With the pantograph noise measured independently, or, estimated by referring to a typical known data, the source data of the aerodynamic noise for this speed, $L_{W,aero}(f, v_0)$, can be obtained.

The source data of total aerodynamic noise at other speeds can then be obtained by applying the spectrum shift, $f = f_0 * v / v_0$, and the speed dependence of the noise sound power level, in the way [21]

$$L_{W,aero}(f,v) = L_{W,aero}\left(f * \frac{v_0}{v}, v_0\right) + 60\log_{10}\left(\frac{v}{v_0}\right), \quad f > 250\,\text{Hz} \qquad (3\text{-}16)$$

$$L_{W,aero}(f,v) = L_{W,aero}\left(f * \frac{v_0}{v}, v_0\right) + 40\log_{10}\left(\frac{v}{v_0}\right), \quad f \le 250\,\text{Hz} \qquad (3\text{-}17)$$

Note: Equations (3-16) and (3-17) could be revised to have a smooth transition from the speed index 6 to 4.

3.2.3 To determine pantograph noise

Pantograph noise can be measured either in a wind tunnel [22] or in field [23], using a microphone array which is usually located 5m to the pantograph. When no such a data available, pantograph noise will be estimated by referring to some known pantograph noise data. Such an exercise was made in [6], as shown in Fig. 3.5.

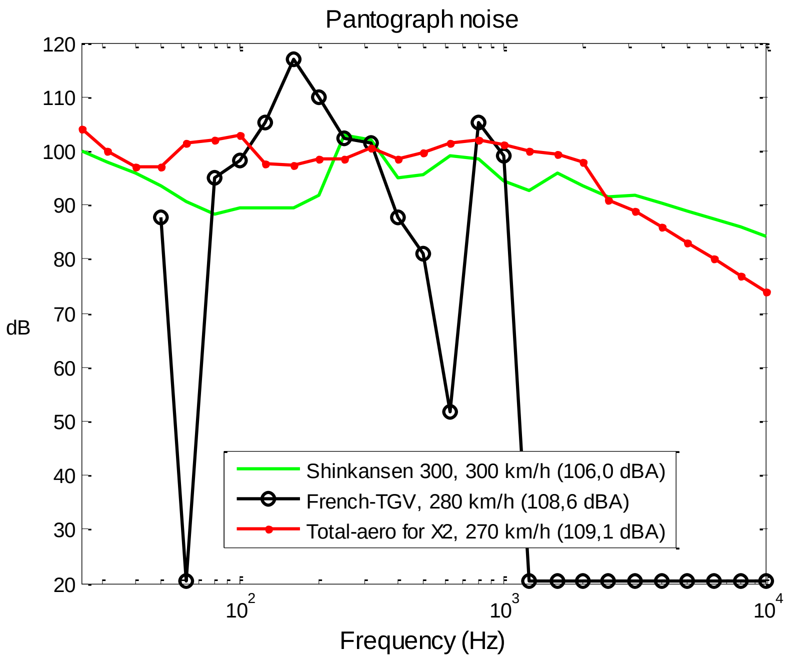


Fig. 3.5. *Comparing with the estimated total sound power level of X2 train aerodynamic noise at 270 km/h, for modeling X2 train pantograph noise, the pantograph noise of Japanese Shinkansen 300 series measured in the wind tunnel [22] seems more suitable than the TGV pantograph noise which is extracted from field measurement [23].*

As shown in Fig. 3.5, for modeling X2 train pantograph noise, it seems that the Japanese data of pantograph noise is more suitable to refer to. Thus, by keeping the tonal feature also adjusting the level to fit the total level of the aerodynamic noise, the X2 train pantograph noise is estimated, as shown in Fig. 3.6. The sound power level of aerodynamic component around bogie areas, obtained by subtracting the pantograph noise component from the total, is also shown in Fig. 3.6, which is about 3 dB stronger than the pantograph noise.

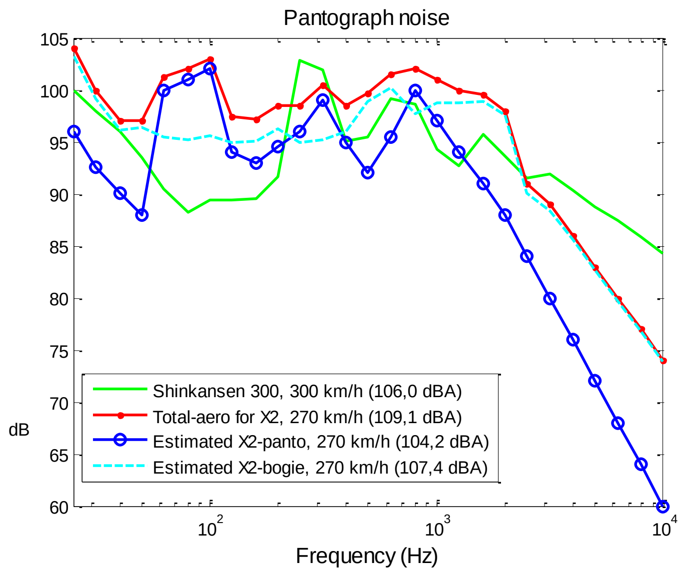


Fig. 3.6. *The sound power levels of the aero-components of X2 train noise at 270 km/h: the estimated total aerodynamic noise, the pantograph noise (of tonal feature) and the aerodynamic component around bogie areas, referring to the pantograph noise of Japanese Shinkansen 300 series [22].*

For railway aerodynamic noise, the spectrum shall shift with train speed. This effect is handled according to

$$f = f_0 * v / v_0 \tag{3-18}$$

Due to this spectrum shift, the equivalent speed dependence (speed exponent) of this noise type becomes different from what is used in the modeling formulation. For instance, for X2 train type, in the sound power description the speed exponent is chosen to be 40 for 25-250 Hz components and 60 for 315-10 000 Hz components for aerodynamic noise around bogie areas, and 60 for all frequency components for pantograph noise. Then, equivalent speed exponent of the dB(A) level becomes 66 for aerodynamic noise around bogie areas, 71.3 for pantograph noise and 67.5 for the total.

In ref. [24], a typical set of noise data for TGV Duplex (which has 10 cars and a length of 200m) was presented. Using the noise data at 100 km/h and at 350 km/h to derive the speed index, together with the noise data at 350 km/h the noise data at 320 km/h can be estimated. By further considering the number of bogies as well as the sound propagation attenuation, the sound power levels for partial aerodynamic sources are derived as, approximately

- Pantograph: 127.7 dB(A)
- Front window/roof: 127.9 dB(A)
- Bogie: 127.5 dB(A)

- Cooling fan, front: 127.2 dB(A)
- Cooling fan, rear: 123.9 dB(A)

Inter-car gap might contribute as high as 131.4 dB. However, by Japanese experience, this component of aerodynamic noise can be reduced to a negligible level. Thus, this component is neglected in the SP acoustic source model. Moreover, to merge the cooling fan noise into the bogie noise, the bogie areas will contribute 131.2 dB(A), which is 3.5 dB(A) over the contribution from the pantograph, similar as the SP estimation (3.2 dB(A)) shown in Fig. 3.6. The only difference is that the front window/roof contribution is not separated from the other partial sources in the SP source model.

In ref. [10] it is proposed to reduce pantograph contribution meanwhile to increase the contribution from bogie areas, according to the supplier's source data.

3.2.4 Tuning of the noise emission data

For aerodynamic noise, the source data for a default HST was made based on X2 train source data while reduced by 6 dB [7].

The discussions made in Sections 2.1 and 2.2 indicate that (1) the noise prediction using the SP source data can well fit the representative European HST data in the important frequency range, when no noise barrier presented; (2) the SP source data for pantograph noise seems 1.5 dB too high compared with the classified data for barrier insertion loss and the supplier's source data.

The big difference below 315 Hz (Fig. 2.2 and Fig. 2.4) indicates that the noise emission data for aerodynamic noise has not properly been described (because this noise type dominates at low frequencies). In the SP acoustic source model, for this low frequency range, the non-pantograph components of aerodynamic noise were modelled by a monopole source, see Eq. (3-17). This monopole source originates from the pressure rise caused by the outward-pushed air (from the track) when a train approaches, and the pressure drop caused by the inward-dragged air when the train recedes. The noise emission data for this monopole source should NOT be reduced when shifting from X2 trains to HSTs because X2 trains and HSTs have a similar cross section area.

Thus, the bogie components of aerodynamic noise will be reduced by 6 dB for $f \geq 315$ Hz, reduced 3 dB at 250 Hz, and no reduction for $f \leq 200$ Hz, when shifting from X2 trains to HSTs. The SP source data for pantograph noise [7] will further be reduced by 1.5 dB, whilst the bogie components of the aerodynamic noise will be correspondingly raised up in order to have the sound power level for the total aerodynamic noise not changed.

Pantographs of Japanese Shinkansen 300 series (operated between 1992 and 2012, with a top speed of 270 km/h) are the ones of an old type. Low noise pantographs developed for Japanese Shinkansen 700 Series are about 12 dB quieter than the 300 series. This fact is useful for estimating how much pantograph noise can be reduced. If assuming that pantographs of X2 trains are acoustically comparable to those of the 300 series, then pantograph noise of X2 trains can at maximum be reduced by about 12 dB if the Japanese design is applied. In this tuned acoustic model, pantograph noise emission data (specified for a default HST) is 7.5 dB lower than that for X2 trains, which is believed not an unrealistic proposal. And, an even lower noise emission data is as believed by the author too risky to be considered at this time.

Moreover, the spectrum data of pantograph noise below 200 Hz was revised by deleting the resonance, referring to the several pantograph noise data found in literature.

3.3 The tuned noise emission data

The tuned SP noise emission data for the four partial noise sources (rail/track radiation, wheel radiation, bogie components of aerodynamic noise and pantograph noise), for a default HST, are given in the following from Table 3.3 to Table 3.6. The noise source data cover a frequency range from 25 Hz to 10 kHz, and a speed range from 30 km/h to 320 km/h.

Table 3.3-1. Sound power level per meter train of rail/track radiation (0,01 m above railhead)

	Speed (km/h)									
Freq. (Hz)	**30**	**40**	**50**	**60**	**70**	**80**	**90**	**100**	**110**	**120**
25	52,4	54,8	55,8	56,6	57,2	57,8	58,3	58,8	59,2	59,6
31,5	54,5	57,1	58,8	59,6	60,2	60,8	61,3	61,8	62,2	62,6
40	56,4	58,3	60,4	62,0	62,7	63,3	63,8	64,3	64,6	65,0
50	58,9	59,4	60,9	62,5	64,1	64,9	65,4	65,9	66,3	66,7
63	62,2	61,9	62,4	63,7	64,7	66,3	67,4	68,0	68,4	68,8
80	66,0	67,0	66,7	66,9	67,8	68,8	69,7	70,9	71,7	72,5
100	71,5	71,2	71,8	71,6	71,4	72,1	72,8	73,6	74,3	75,2
125	75,0	72,1	72,2	72,8	72,6	72,5	72,4	73,1	73,6	74,3
160	77,2	75,5	73,3	72,9	73,8	73,9	73,7	73,6	73,5	73,8
200	77,9	79,3	77,7	75,8	75,0	75,5	76,2	76,1	76,0	75,9
250	77,8	81,2	82,1	81,0	79,2	78,2	77,6	78,2	78,8	78,9
315	79,4	83,4	85,9	86,9	86,6	85,0	83,6	82,9	82,5	82,7
400	74,8	79,2	82,3	84,5	85,8	85,9	85,7	84,3	83,3	82,3
500	71,4	78,7	82,0	84,5	86,5	87,9	88,9	88,7	88,6	87,7
630	66,2	73,4	78,8	81,6	83,6	85,6	87,0	88,1	88,9	89,1
800	62,2	69,2	74,7	79,6	82,1	84,0	85,5	87,1	88,2	89,3
1000	62,3	68,0	73,4	77,6	82,2	84,9	86,7	88,2	89,4	90,7
1250	60,7	64,2	68,7	73,1	76,3	80,4	83,9	85,7	87,1	88,5
1600	61,6	64,1	66,8	70,3	73,8	77,2	79,4	82,7	85,4	87,6
2000	62,4	64,9	66,9	68,8	71,4	74,5	77,2	79,9	81,5	84,1
2500	56,6	59,4	61,4	62,9	64,3	66,4	68,5	71,0	73,1	75,3
3150	56,8	59,2	61,3	62,9	64,1	65,4	66,4	68,2	69,8	71,7
4000	57,6	60,1	62,0	63,7	65,1	66,3	67,2	68,2	69,0	70,2
5000	59,5	62,1	64,0	65,4	66,9	68,2	69,3	70,2	70,9	71,8
6300	58,6	60,9	63,0	64,6	65,5	67,0	68,1	69,1	69,9	70,7
8000	58,9	61,5	63,3	64,9	66,4	67,4	68,1	69,3	70,1	71,0
10000	62,4	65,0	67,0	68,4	69,7	71,0	72,1	72,8	73,4	74,3
A-weighted	**78,4**	**82,7**	**85,8**	**88,1**	**90,1**	**91,8**	**93,4**	**94,6**	**95,7**	**96,8**

Table 3.3-2. Sound power level per meter train of rail/track radiation (0,01 m above railhead)

Freq. (Hz)	**Speed (km/h)**									
	130	**140**	**150**	**160**	**170**	**180**	**190**	**200**	**210**	**220**
25	59,8	60,2	60,5	60,8	61,0	61,3	61,6	61,8	62,0	62,2
31,5	62,9	63,3	63,6	63,9	64,0	64,3	64,5	64,8	65,0	65,2
40	65,4	65,7	66,0	66,3	66,5	66,8	67,1	67,3	67,4	67,6
50	66,9	67,3	67,6	67,9	68,1	68,4	68,7	68,9	69,1	69,3
63	69,1	69,4	69,7	70,0	70,2	70,5	70,7	71,0	71,2	71,4
80	72,9	73,2	73,5	73,8	74,0	74,3	74,5	74,8	74,9	75,1
100	75,9	76,8	77,3	77,6	77,8	78,1	78,4	78,6	78,7	79,0
125	74,8	75,4	76,2	76,9	77,4	78,1	78,4	78,6	78,8	79,0
160	74,3	74,7	75,2	75,7	76,1	76,5	77,2	77,8	78,1	78,6
200	75,8	75,7	76,0	76,4	76,7	77,1	77,5	77,9	78,2	78,6
250	78,8	78,7	78,6	78,6	78,5	78,5	78,8	79,1	79,4	79,7
315	83,1	83,6	83,6	83,5	83,5	83,4	83,3	83,3	83,3	83,2
400	81,9	81,5	81,6	82,1	82,4	82,8	82,7	82,6	82,6	82,5
500	86,9	85,9	85,2	84,9	84,6	84,2	84,6	84,9	85,2	85,5
630	88,9	88,8	88,0	87,2	86,6	85,8	85,4	85,1	84,9	84,6
800	90,0	90,7	90,9	90,7	90,7	90,6	89,9	89,1	88,8	88,1
1000	91,6	92,7	93,5	94,1	94,6	95,1	95,0	94,9	94,9	94,8
1250	89,4	90,4	91,5	92,4	93,0	93,9	94,4	94,9	95,3	95,7
1600	88,9	90,1	91,2	92,1	92,7	93,5	94,4	95,1	95,5	96,2
2000	86,6	88,7	90,4	91,4	92,3	93,3	94,1	94,8	95,3	95,9
2500	76,6	78,5	80,6	82,6	84,3	86,2	87,1	87,9	88,6	89,4
3150	73,5	75,2	77,1	78,7	79,4	80,9	82,7	84,3	85,6	87,1
4000	71,6	72,8	74,4	75,9	77,2	78,6	80,0	81,3	81,7	82,9
5000	72,3	73,1	74,1	75,3	76,2	77,3	78,6	79,8	80,8	81,9
6300	71,2	71,9	72,6	73,2	73,6	74,2	75,1	76,0	76,8	77,6
8000	71,8	72,4	73,0	73,6	74,0	74,5	75,0	75,5	75,8	76,3
10000	74,9	75,8	76,5	77,1	77,6	78,1	78,6	79,0	79,3	79,7
A-weighted	**97,7**	**98,7**	**99,5**	**100,2**	**100,8**	**101,5**	**102,0**	**102,4**	**102,8**	**103,3**

Table 3.3-3. Sound power level per meter train of <u>rail/track radiation</u> (0,01 m above railhead)

Freq. (Hz)	Speed (km/h) 230	240	250	260	270	280	290	300	310	320
25	62,4	62,6	62,8	62,9	63,1	63,3	63,4	63,6	63,7	63,9
31,5	65,4	65,6	65,8	65,9	66,1	66,3	66,4	66,6	66,7	66,9
40	67,8	68,0	68,2	68,4	68,5	68,7	68,8	69,0	69,2	69,3
50	69,5	69,7	69,9	69,9	70,1	70,3	70,4	70,6	70,8	70,9
63	71,6	71,8	72,0	72,1	72,3	72,5	72,6	72,8	72,9	73,1
80	75,3	75,5	75,7	75,9	76,0	76,2	76,4	76,5	76,7	76,8
100	79,2	79,4	79,6	79,6	79,8	80,0	80,1	80,3	80,4	80,6
125	79,2	79,4	79,6	79,7	79,9	80,0	80,2	80,4	80,5	80,6
160	79,2	79,4	79,6	79,7	79,9	80,1	80,2	80,4	80,5	80,7
200	79,0	79,5	80,0	80,2	80,6	81,1	81,4	81,6	81,8	81,9
250	80,0	80,4	80,7	80,9	81,2	81,5	81,8	82,3	82,6	83,0
315	83,3	83,6	83,8	84,0	84,3	84,5	84,8	85,0	85,3	85,5
400	82,5	82,4	82,4	82,4	82,3	82,3	82,3	82,5	82,8	83,0
500	85,6	85,5	85,5	85,5	85,4	85,4	85,3	85,3	85,3	85,2
630	84,6	84,8	85,1	85,3	85,5	85,8	85,8	85,8	85,7	85,7
800	87,5	87,2	87,0	86,8	86,6	86,4	86,3	86,5	86,7	86,9
1000	94,5	93,9	93,3	93,1	92,6	92,1	91,6	91,4	91,2	91,1
1250	95,9	95,8	95,7	95,7	95,6	95,5	95,2	94,7	94,2	93,8
1600	96,9	97,3	97,7	98,1	98,3	98,7	98,9	98,9	98,8	98,8
2000	96,6	97,2	97,9	98,1	98,7	99,2	99,7	100,1	100,4	100,6
2500	90,1	90,7	91,3	91,6	92,1	92,7	93,2	93,7	94,2	94,7
3150	88,3	89,0	89,7	90,2	90,8	91,4	92,0	92,5	92,9	93,4
4000	84,1	85,5	86,8	88,0	89,0	90,1	91,2	91,8	92,3	92,8
5000	83,1	84,2	85,2	85,4	86,4	87,3	88,3	89,4	90,4	91,4
6300	78,5	79,6	80,5	81,3	82,2	83,1	84,0	84,9	85,7	86,5
8000	76,7	77,5	78,2	78,9	79,5	80,1	80,8	81,7	82,4	83,2
10000	80,2	80,6	81,0	81,2	81,6	81,9	82,3	83,0	83,6	84,1
A-weighted	**103,7**	**104,0**	**104,3**	**104,6**	**104,9**	**105,3**	**105,6**	**105,8**	**106,0**	**106,2**

Table 3.4-1. Sound power level per meter train of wheel radiation (0,5 m above railhead)

Freq. (Hz)	Speed (km/h) 30	40	50	60	70	80	90	100	110	120
25	27,4	29,8	30,8	31,6	32,2	32,8	33,3	33,8	34,2	34,6
31,5	27,5	30,1	31,8	32,6	33,2	33,8	34,3	34,8	35,2	35,6
40	29,9	31,8	33,9	35,5	36,2	36,8	37,3	37,8	38,1	38,5
50	33,9	34,4	35,9	37,5	39,1	39,9	40,4	40,9	41,3	41,7
63	38,8	38,5	39,0	40,3	41,3	42,9	44,0	44,6	45,0	45,4
80	44,1	45,1	44,8	45,0	45,9	46,9	47,8	49,0	49,8	50,6
100	51,5	51,2	51,8	51,6	51,4	52,1	52,8	53,6	54,3	55,2
125	56,6	53,7	53,8	54,4	54,2	54,1	54,0	54,7	55,2	55,9
160	60,4	58,7	56,5	56,1	57,0	57,1	56,9	56,8	56,7	57,0
200	62,8	64,2	62,6	60,7	59,9	60,4	61,1	61,0	60,9	60,8
250	65,6	69,0	69,9	68,8	67,0	66,0	65,4	66,0	66,6	66,7
315	75,4	79,4	81,9	82,9	82,6	81,0	79,6	78,9	78,5	78,7
400	68,4	72,8	75,9	78,1	79,4	79,5	79,3	77,9	76,9	75,9
500	59,5	66,8	70,1	72,6	74,6	76,0	77,0	76,8	76,7	75,8
630	55,2	62,4	67,8	70,6	72,6	74,6	76,0	77,1	77,9	78,1
800	54,6	61,6	67,1	72,0	74,5	76,4	77,9	79,5	80,6	81,7
1000	51,6	57,3	62,7	66,9	71,5	74,2	76,0	77,5	78,7	80,0
1250	50,3	53,8	58,3	62,7	65,9	70,0	73,5	75,3	76,7	78,1
1600	53,9	56,4	59,1	62,6	66,1	69,5	71,7	75,0	77,7	79,9
2000	60,7	63,2	65,2	67,1	69,7	72,8	75,5	78,2	79,8	82,4
2500	64,4	67,2	69,2	70,7	72,1	74,2	76,3	78,8	80,9	83,1
3150	63,1	65,5	67,6	69,2	70,4	71,7	72,7	74,5	76,1	78,0
4000	61,1	63,6	65,5	67,2	68,6	69,8	70,7	71,7	72,5	73,7
5000	62,5	65,1	67,0	68,4	69,9	71,2	72,3	73,2	73,9	74,8
6300	65,3	67,6	69,7	71,3	72,2	73,7	74,8	75,8	76,6	77,4
8000	67,6	70,2	72,0	73,6	75,1	76,1	76,8	78,0	78,8	79,7
10000	69,8	72,4	74,4	75,8	77,1	78,4	79,5	80,2	80,8	81,7
A-weighted	**75,7**	**78,9**	**81,3**	**83,1**	**84,5**	**85,8**	**87,1**	**88,6**	**89,8**	**91,4**

Table 3.4-2. Sound power level per meter train of wheel radiation (0,5 m above railhead)

Freq. (Hz)	Speed (km/h)									
	130	**140**	**150**	**160**	**170**	**180**	**190**	**200**	**210**	**220**
25	34,8	35,2	35,5	35,8	36,0	36,3	36,6	36,8	37,0	37,2
31,5	35,9	36,3	36,6	36,9	37,0	37,3	37,5	37,8	38,0	38,2
40	38,9	39,2	39,5	39,8	40,0	40,3	40,6	40,8	40,9	41,1
50	41,9	42,3	42,6	42,9	43,1	43,4	43,7	43,9	44,1	44,3
63	45,7	46,0	46,3	46,6	46,8	47,1	47,3	47,6	47,8	48,0
80	51,0	51,3	51,6	51,9	52,1	52,4	52,6	52,9	53,0	53,2
100	55,9	56,8	57,3	57,6	57,8	58,1	58,4	58,6	58,7	59,0
125	56,4	57,0	57,8	58,5	59,0	59,7	60,0	60,2	60,4	60,6
160	57,5	57,9	58,4	58,9	59,3	59,7	60,4	61,0	61,3	61,8
200	60,7	60,6	60,9	61,3	61,6	62,0	62,4	62,8	63,1	63,5
250	66,6	66,5	66,4	66,4	66,3	66,3	66,6	66,9	67,2	67,5
315	79,1	79,6	79,6	79,5	79,5	79,4	79,3	79,3	79,3	79,2
400	75,5	75,1	75,2	75,7	76,0	76,4	76,3	76,2	76,2	76,1
500	75,0	74,0	73,3	73,0	72,7	72,3	72,7	73,0	73,3	73,6
630	77,9	77,8	77,0	76,2	75,6	74,8	74,4	74,1	73,9	73,6
800	82,4	83,1	83,3	83,1	83,1	83,0	82,3	81,5	81,2	80,5
1000	80,9	82,0	82,8	83,4	83,9	84,4	84,3	84,2	84,2	84,1
1250	79,0	80,0	81,1	82,0	82,6	83,5	84,0	84,5	84,9	85,3
1600	81,2	82,4	83,5	84,4	85,0	85,8	86,7	87,4	87,8	88,5
2000	84,9	87,0	88,7	89,7	90,6	91,6	92,4	93,1	93,6	94,2
2500	84,4	86,3	88,4	90,4	92,1	94,0	94,9	95,7	96,4	97,2
3150	79,8	81,5	83,4	85,0	85,7	87,2	89,0	90,6	91,9	93,4
4000	75,1	76,3	77,9	79,4	80,7	82,1	83,5	84,8	85,2	86,4
5000	75,3	76,1	77,1	78,3	79,2	80,3	81,6	82,8	83,8	84,9
6300	77,9	78,6	79,3	79,9	80,3	80,9	81,8	82,7	83,5	84,3
8000	80,5	81,1	81,7	82,3	82,7	83,2	83,7	84,2	84,5	85,0
10000	82,3	83,2	83,9	84,5	85,0	85,5	86,0	86,4	86,7	87,1
A-weighted	**92,6**	**94,1**	**95,5**	**96,7**	**97,7**	**99,0**	**99,9**	**100,7**	**101,4**	**102,2**

Table 3.4-3. Sound power level per meter train of wheel radiation (0,5 m above railhead)

	Speed (km/h)									
Freq. (Hz)	**230**	**240**	**250**	**260**	**270**	**280**	**290**	**300**	**310**	**320**
25	37,4	37,6	37,8	37,9	38,1	38,3	38,4	38,6	38,7	38,9
31,5	38,4	38,6	38,8	38,9	39,1	39,3	39,4	39,6	39,7	39,9
40	41,3	41,5	41,7	41,9	42,0	42,2	42,3	42,5	42,7	42,8
50	44,5	44,7	44,9	44,9	45,1	45,3	45,4	45,6	45,8	45,9
63	48,2	48,4	48,6	48,7	48,9	49,1	49,2	49,4	49,5	49,7
80	53,4	53,6	53,8	54,0	54,1	54,3	54,5	54,6	54,8	54,9
100	59,2	59,4	59,6	59,6	59,8	60,0	60,1	60,3	60,4	60,6
125	60,8	61,0	61,2	61,3	61,5	61,6	61,8	62,0	62,1	62,2
160	62,4	62,6	62,8	62,9	63,1	63,3	63,4	63,6	63,7	63,9
200	63,9	64,4	64,9	65,1	65,5	66,0	66,3	66,5	66,7	66,8
250	67,8	68,2	68,5	68,7	69,0	69,3	69,6	70,1	70,4	70,8
315	79,3	79,6	79,8	80,0	80,3	80,5	80,8	81,0	81,3	81,5
400	76,1	76,0	76,0	76,0	75,9	75,9	75,9	76,1	76,4	76,6
500	73,7	73,6	73,6	73,6	73,5	73,5	73,4	73,4	73,4	73,3
630	73,6	73,8	74,1	74,3	74,5	74,8	74,8	74,8	74,7	74,7
800	79,9	79,6	79,4	79,2	79,0	78,8	78,7	78,9	79,1	79,3
1000	83,8	83,2	82,6	82,4	81,9	81,4	80,9	80,7	80,5	80,4
1250	85,5	85,4	85,3	85,3	85,2	85,1	84,8	84,3	83,8	83,4
1600	89,2	89,6	90,0	90,4	90,6	91,0	91,2	91,2	91,1	91,1
2000	94,9	95,5	96,2	96,4	97,0	97,5	98,0	98,4	98,7	98,9
2500	97,9	98,5	99,1	99,4	99,9	100,5	101,0	101,5	102,0	102,5
3150	94,6	95,3	96,0	96,5	97,1	97,7	98,3	98,8	99,2	99,7
4000	87,6	89,0	90,3	91,5	92,5	93,6	94,7	95,3	95,8	96,3
5000	86,1	87,2	88,2	88,4	89,4	90,3	91,3	92,4	93,4	94,4
6300	85,2	86,3	87,2	88,0	88,9	89,8	90,7	91,6	92,4	93,2
8000	85,4	86,2	86,9	87,6	88,2	88,8	89,5	90,4	91,1	91,9
10000	87,6	88,0	88,4	88,6	89,0	89,3	89,7	90,4	91,0	91,5
A-weighted	**103,0**	**103,7**	**104,3**	**104,7**	**105,3**	**105,9**	**106,5**	**106,9**	**107,4**	**107,9**

Table 3.5-1. Sound power level per meter train of aerodynamic noise around the bogie areas (0,5 m above railhead)

	Speed (km/h)									
Freq. (Hz)	**30**	**40**	**50**	**60**	**70**	**80**	**90**	**100**	**110**	**120**
25	61,4	65,4	69,2	75,1	80,4	82,2	83,8	85,3	86,2	86,0
31,5	62,4	66,4	69,3	72,3	75,8	81,3	84,7	86,1	87,4	88,6
40	62,4	67,1	70,3	72,8	74,8	77,3	80,5	84,8	88,3	89,4
50	61,8	67,7	70,9	73,4	75,8	77,4	79,2	81,1	83,4	87,0
63	63,1	66,6	71,5	74,4	76,0	78,3	80,0	81,3	82,6	84,2
80	65,2	67,8	70,5	74,3	77,7	79,0	80,3	82,1	83,7	84,6
100	66,2	69,7	71,6	73,8	76,4	79,6	81,7	82,7	83,7	85,2
125	65,4	71,3	73,6	75,0	76,7	78,6	80,9	83,3	85,2	85,9
160	63,6	70,6	75,1	77,2	78,4	79,8	81,0	82,5	83,9	86,0
200	61,7	69,0	74,4	78,2	80,6	81,7	82,5	83,6	84,6	85,7
250	54,3	64,0	69,9	74,4	77,7	80,2	81,6	82,5	83,2	84,0
315	27,4	41,0	49,9	56,4	61,6	65,6	68,8	71,6	73,7	75,2
400	25,0	35,2	46,3	54,3	59,5	64,1	68,2	71,3	74,1	76,3
500	22,1	33,1	41,0	49,9	57,9	62,2	66,4	69,9	73,4	76,0
630	19,1	30,2	38,8	45,5	51,4	59,1	64,6	68,0	71,3	74,5
800	16,2	27,1	35,9	43,1	48,8	53,3	58,4	64,4	69,6	72,4
1000	13,2	24,2	32,9	40,1	46,2	51,1	55,6	59,1	62,8	68,0
1250	10,7	21,5	30,0	37,3	43,2	48,4	53,1	57,0	60,6	63,6
1600	8,7	18,5	27,0	34,2	40,1	45,1	49,9	53,9	57,7	61,1
2000	6,7	16,5	24,3	31,3	37,3	42,3	47,0	51,0	54,8	58,2
2500	4,7	14,7	22,3	28,8	34,3	39,5	44,3	48,1	51,9	55,4
3150	2,7	12,7	20,5	26,9	32,1	36,7	41,2	45,2	49,1	52,5
4000	0,7	10,5	18,3	24,8	30,2	34,6	38,8	42,4	45,9	49,3
5000	-1,3	8,6	16,3	22,8	28,2	32,8	37,0	40,4	43,8	46,8
6300	-3,3	6,7	14,3	20,8	26,1	30,7	34,9	38,5	41,9	45,0
8000	-5,3	4,5	12,3	18,8	24,0	28,6	32,8	36,4	39,8	42,8
10000	-6,3	3,2	11,1	17,8	23,8	27,3	32,4	35,1	39,6	41,9
A-weighted	**56,3**	**63,1**	**67,8**	**71,2**	**73,8**	**75,8**	**77,4**	**79,1**	**80,8**	**82,7**

Table 3.5-2. Sound power level per meter train of aerodynamic noise around the bogie areas (0,5 m above railhead)

	Speed (km/h)									
Freq. (Hz)	**130**	**140**	**150**	**160**	**170**	**180**	**190**	**200**	**210**	**220**
25	86,1	86,5	87,8	88,9	89,9	91,7	93,3	94,6	96,0	97,6
31,5	89,8	90,2	90,0	90,1	89,8	90,8	91,7	92,6	93,5	94,7
40	90,5	91,5	92,5	93,5	94,3	94,2	94,1	94,2	94,0	94,1
50	90,3	92,4	93,3	94,2	95,0	95,7	96,5	97,3	98,0	98,1
63	85,6	87,7	90,7	93,2	95,9	96,6	97,3	98,0	98,7	99,3
80	85,6	86,6	87,9	89,1	90,2	92,3	94,6	96,7	98,8	100,2
100	86,6	87,6	88,4	89,1	89,8	90,9	91,9	92,7	93,7	95,0
125	86,7	87,7	88,9	90,0	91,0	91,6	92,2	92,7	93,2	94,0
160	87,7	89,0	89,6	90,3	90,8	91,7	92,6	93,5	94,3	95,0
200	86,8	88,1	89,6	90,8	91,9	92,5	93,0	93,5	94,0	94,6
250	84,8	85,6	86,5	87,3	88,1	89,3	90,4	91,2	91,7	92,1
315	76,8	78,1	79,4	80,7	81,9	83,0	84,1	85,1	86,0	87,1
400	78,4	80,0	81,2	82,5	83,5	84,5	85,6	86,7	87,6	88,5
500	78,3	80,4	82,2	83,8	85,3	86,3	87,2	88,3	89,1	89,9
630	77,1	79,7	81,7	83,6	85,4	86,9	88,3	89,6	90,8	91,8
800	75,0	77,6	80,1	82,2	84,5	86,3	87,9	89,4	90,8	92,1
1000	72,5	76,0	78,2	80,3	82,3	84,4	86,4	88,0	89,8	91,4
1250	66,2	69,8	73,8	77,4	80,8	82,7	84,5	86,1	87,7	89,4
1600	64,0	66,9	69,2	71,3	73,4	76,5	79,6	82,4	85,3	87,6
2000	61,3	64,2	67,0	69,2	71,6	73,6	75,5	77,1	78,8	80,9
2500	58,3	61,3	64,0	66,5	68,9	71,2	73,3	75,0	77,0	78,7
3150	55,4	58,3	61,1	63,4	65,8	68,1	70,2	72,2	74,1	76,0
4000	52,4	55,4	58,1	60,4	62,8	65,1	67,2	69,0	71,0	72,8
5000	49,6	52,4	55,1	57,6	60,0	62,3	64,4	66,2	68,1	70,0
6300	47,5	50,2	52,6	54,8	56,9	59,2	61,4	63,3	65,3	67,1
8000	45,6	48,2	50,7	52,7	54,8	56,8	58,7	60,5	62,2	63,9
10000	44,0	47,9	49,7	51,4	53,0	56,4	57,8	59,2	60,5	63,7
A-weighted	**84,5**	**86,4**	**88,2**	**89,8**	**91,6**	**93,1**	**94,5**	**95,9**	**97,3**	**98,7**

Table 3.5-3. Sound power level per meter train of aerodynamic noise around the bogie areas (0,5 m above railhead)

	Speed (km/h)									
Freq. (Hz)	**230**	**240**	**250**	**260**	**270**	**280**	**290**	**300**	**310**	**320**
25	99,1	100,6	101,7	103,1	104,5	105,4	106,3	107,1	107,8	108,6
31,5	96,0	97,2	98,1	99,2	100,3	101,6	102,8	104,0	104,8	105,9
40	94,9	95,6	96,3	96,9	97,6	98,6	99,6	100,6	101,2	102,1
50	98,0	97,8	97,9	97,7	97,5	98,1	98,6	99,2	99,7	100,2
63	99,9	100,5	101,1	101,7	102,2	102,0	101,8	101,7	101,8	101,6
80	100,8	101,4	101,9	102,4	102,9	103,4	103,9	104,3	104,8	105,3
100	97,0	98,8	100,4	102,1	103,8	104,3	104,7	105,1	105,6	106,0
125	94,9	95,6	96,3	97,0	97,7	99,4	101,0	102,5	103,8	105,2
160	95,4	95,9	96,3	96,7	97,0	97,6	98,3	98,9	99,4	99,9
200	95,3	96,1	96,8	97,5	98,1	98,4	98,7	99,0	99,3	99,5
250	92,6	93,0	93,5	93,9	94,2	94,9	95,5	96,1	96,7	97,2
315	88,3	89,4	90,3	91,0	91,4	92,7	93,7	94,6	95,5	96,3
400	89,4	90,2	91,1	91,8	92,4	93,4	94,4	95,2	96,0	96,7
500	90,8	91,6	92,5	93,2	93,9	94,7	95,4	96,0	96,7	97,3
630	92,5	93,3	94,2	94,8	95,5	96,1	96,8	97,5	98,2	98,8
800	93,3	94,4	95,4	96,4	97,4	98,0	98,6	99,2	100,0	100,5
1000	92,8	94,0	95,2	96,3	97,5	98,4	99,3	100,2	101,1	101,9
1250	91,1	92,3	93,8	95,3	96,7	97,8	98,8	99,8	100,8	101,7
1600	89,1	90,5	91,7	93,0	94,2	95,6	96,9	98,2	99,1	100,3
2000	83,6	86,1	88,3	90,6	92,9	94,0	95,2	96,3	97,3	98,3
2500	80,2	81,7	83,0	84,3	85,6	87,8	89,9	91,9	93,6	95,5
3150	77,8	79,4	80,7	82,3	83,8	85,1	86,3	87,4	88,4	89,5
4000	74,6	76,3	77,8	79,3	80,9	82,3	83,7	85,0	86,0	87,3
5000	71,7	73,4	74,8	76,4	77,9	79,4	80,8	82,1	83,3	84,5
6300	68,9	70,6	71,9	73,4	74,9	76,4	77,8	79,1	80,2	81,5
8000	65,7	67,4	68,9	70,5	72,0	73,4	74,8	76,2	77,2	78,4
10000	64,8	65,9	67,0	68,0	69,0	72,9	73,8	74,7	75,6	76,4
A-weighted	**99,9**	**101,1**	**102,2**	**103,4**	**104,5**	**105,5**	**106,5**	**107,5**	**108,4**	**109,3**

Table 3.6-1. Sound power level per meter train of pantograph noise[*] (5 m above railhead)

	Speed (km/h)									
Freq. (Hz)	**30**	**40**	**50**	**60**	**70**	**80**	**90**	**100**	**110**	**120**
25	30,8	36,0	40,6	44,6	48,2	51,3	54,1	56,6	59,0	61,2
31,5	34,1	37,8	41,8	45,4	48,8	52,0	54,7	57,1	59,3	61,4
40	33,2	40,9	43,8	47,0	49,9	52,8	55,4	57,8	60,0	62,0
50	28,2	41,8	46,7	48,8	51,5	54,0	56,3	58,6	60,6	62,7
63	28,3	36,6	47,4	52,1	53,6	55,9	57,9	59,9	61,7	63,5
80	32,8	35,2	42,1	51,2	57,9	58,9	60,0	61,8	63,5	65,0
100	33,7	39,4	41,0	46,2	53,4	59,9	63,8	64,7	65,4	66,9
125	30,7	42,0	45,2	46,2	49,0	54,8	60,7	65,7	69,5	70,0
160	27,7	38,7	47,5	50,9	51,9	53,2	55,6	60,2	64,6	69,3
200	24,7	35,7	44,5	51,8	56,5	57,4	57,9	59,1	60,5	64,3
250	21,2	33,0	41,5	48,8	54,8	60,0	62,4	63,2	63,6	64,3
315	17,2	29,6	38,7	46,0	51,7	56,9	61,7	65,8	68,3	68,6
400	13,2	25,3	35,1	42,8	48,8	53,7	58,5	62,5	66,4	69,8
500	9,2	21,4	31,1	39,2	45,8	51,0	55,8	59,5	63,4	66,8
630	5,2	17,6	27,1	35,2	41,9	47,7	52,7	56,8	60,6	64,0
800	1,2	13,3	23,1	31,2	37,7	43,4	48,6	53,2	57,4	60,8
1000	-2,8	9,4	19,1	27,2	34,0	39,5	44,8	49,2	53,5	57,3
1250	-5,8	5,7	15,3	23,4	30,0	35,8	41,1	45,3	49,6	53,4
1600	-7,8	2,0	11,1	19,2	25,7	31,4	36,6	41,2	45,5	49,3
2000	-9,8	0,0	7,8	15,2	22,0	27,5	32,8	37,2	41,5	45,3
2500	-11,8	-1,8	5,8	12,3	18,0	23,8	29,1	33,3	37,6	41,4
3150	-13,8	-3,8	4,0	10,4	15,6	20,2	24,9	29,5	33,8	37,6
4000	-15,8	-6,0	1,8	8,3	13,7	18,1	22,3	25,9	29,5	33,3
5000	-17,8	-7,9	-0,2	6,3	11,7	16,3	20,5	23,9	27,3	30,3
6300	-19,8	-9,8	-2,2	4,3	9,6	14,2	18,4	22,0	25,4	28,5
8000	-21,8	-12,0	-4,2	2,3	7,5	12,1	16,3	19,9	23,3	26,3
10000	-22,8	-13,3	-5,4	1,3	7,3	10,8	15,9	18,6	23,1	25,4
A-weighted	**22,2**	**32,8**	**40,8**	**47,3**	**52,8**	**57,3**	**61,3**	**64,8**	**68,0**	**70,8**

[*] A pantograph can also be treated as a point source – in the case $10*\log_{10}(165) = 22.2$ (dB) should be added to the tabular values.

Table 3.6-2. Sound power level per meter train of pantograph noise[*] (5 m above railhead)

Freq. (Hz)	Speed (km/h)									
	130	**140**	**150**	**160**	**170**	**180**	**190**	**200**	**210**	**220**
25	63,2	65,1	67,0	68,7	70,3	72,9	75,2	77,0	79,1	81,1
31,5	63,4	65,3	67,0	68,6	70,1	71,7	73,1	74,5	75,8	77,6
40	63,9	65,6	67,3	68,9	70,4	71,8	73,1	74,5	75,7	76,9
50	64,6	66,3	67,8	69,3	70,7	72,1	73,4	74,7	75,9	77,0
63	65,3	66,9	68,5	70,0	71,4	72,7	74,0	75,2	76,3	77,4
80	66,6	68,0	69,4	70,9	72,1	73,4	74,7	75,9	77,0	78,1
100	68,3	69,6	70,9	72,1	73,2	74,4	75,5	76,7	77,7	78,7
125	70,8	71,5	72,7	73,9	74,9	75,9	76,9	77,9	78,8	79,7
160	72,9	75,9	76,3	77,0	77,3	78,0	79,0	79,9	80,7	81,5
200	67,7	71,4	75,1	77,9	81,2	81,9	82,2	82,8	83,1	83,5
250	65,2	67,1	70,1	72,9	75,7	78,8	81,6	83,7	86,4	87,6
315	69,4	69,7	70,2	71,0	71,5	74,0	76,4	78,5	80,7	83,1
400	72,9	74,5	74,8	75,5	75,6	76,0	76,4	77,1	77,5	78,5
500	69,9	72,9	75,6	78,1	80,3	80,4	80,6	81,3	81,4	81,7
630	66,8	69,8	72,5	75,0	77,4	79,7	81,9	83,8	85,8	86,4
800	63,9	66,9	69,6	71,8	74,2	76,5	78,7	80,6	82,5	84,4
1000	60,7	63,9	66,6	69,1	71,6	73,8	76,0	77,6	79,5	81,4
1250	56,7	60,1	63,1	65,9	68,6	70,8	73,0	74,9	76,9	78,8
1600	52,4	55,8	58,8	61,4	64,1	66,7	69,1	71,2	73,4	75,4
2000	48,7	52,1	55,1	57,6	60,3	62,9	65,2	67,2	69,4	71,5
2500	44,7	48,1	51,1	53,9	56,6	59,1	61,5	63,4	65,6	67,7
3150	40,7	44,1	47,1	49,7	52,4	55,0	57,4	59,5	61,7	63,8
4000	36,7	40,1	43,1	45,6	48,3	50,9	53,2	55,2	57,4	59,5
5000	33,1	36,1	39,1	41,9	44,6	47,1	49,5	51,4	53,6	55,7
6300	31,0	33,7	36,1	38,3	40,4	43,0	45,4	47,5	49,7	51,8
8000	29,1	31,7	34,2	36,1	38,3	40,3	42,2	44,0	45,7	47,5
10000	27,5	31,4	33,2	34,9	36,5	39,9	41,3	42,7	44,0	47,2
A-weighted	**73,5**	**76,0**	**78,1**	**80,2**	**82,3**	**83,9**	**85,5**	**87,2**	**88,9**	**90,2**

[*] A pantograph can also be treated as a point source – in the case $10*\log_{10}(165) = 22.2$ (dB) should be added to the tabular values.

Table 3.6-3. Sound power level per meter train of pantograph noise[*] (5 m above railhead)

Freq. (Hz)	Speed (km/h) 230	240	250	260	270	280	290	300	310	320
25	82,9	84,6	86,1	87,7	89,3	90,6	91,8	93,0	94,1	95,2
31,5	79,5	81,3	82,7	84,4	86,0	87,5	89,0	90,3	91,5	92,8
40	78,1	79,2	80,3	81,4	82,4	84,0	85,5	86,9	87,9	89,3
50	78,2	79,2	80,3	81,3	82,2	83,2	84,1	85,0	85,9	86,8
63	78,5	79,5	80,5	81,5	82,4	83,3	84,2	85,0	85,9	86,7
80	79,1	80,1	81,0	81,9	82,8	83,7	84,5	85,4	86,2	87,0
100	79,7	80,7	81,7	82,6	83,5	84,3	85,1	85,9	86,7	87,4
125	80,6	81,7	82,5	83,3	84,1	84,9	85,8	86,6	87,3	88,1
160	82,3	83,1	83,9	84,6	85,3	86,0	86,8	87,5	88,3	89,0
200	84,2	85,0	85,7	86,4	87,0	87,7	88,3	88,9	89,6	90,2
250	87,8	88,1	88,6	88,8	89,0	89,6	90,2	90,8	91,4	91,9
315	85,5	87,7	89,3	91,4	93,5	93,7	93,9	94,1	94,5	94,7
400	80,5	82,4	84,1	85,8	87,5	89,5	91,4	93,2	94,3	96,0
500	82,0	82,4	82,9	83,2	83,5	85,1	86,7	88,2	89,5	90,9
630	86,5	86,7	87,3	87,4	87,5	87,8	88,0	88,3	88,8	89,1
800	86,2	87,9	89,4	91,0	92,5	92,6	92,7	92,8	93,4	93,5
1000	83,2	84,9	86,4	88,0	89,5	91,0	92,4	93,7	94,9	96,2
1250	80,5	81,8	83,4	85,0	86,5	88,0	89,4	90,7	91,9	93,2
1600	77,2	78,9	80,4	82,0	83,5	85,0	86,4	87,7	88,6	89,8
2000	73,5	75,4	77,1	78,8	80,5	82,0	83,4	84,7	85,9	87,2
2500	69,6	71,5	73,1	74,8	76,5	78,1	79,7	81,2	82,5	83,9
3150	65,8	67,6	69,1	70,8	72,5	74,1	75,7	77,2	78,4	79,8
4000	61,5	63,4	65,1	66,8	68,5	70,1	71,7	73,2	74,2	75,6
5000	57,6	59,5	61,1	62,8	64,5	66,1	67,7	69,2	70,5	71,9
6300	53,8	55,6	57,1	58,8	60,5	62,1	63,7	65,2	66,4	67,8
8000	49,5	51,4	53,1	54,8	56,5	58,1	59,7	61,2	62,2	63,6
10000	48,3	49,4	50,5	51,5	52,5	57,4	58,4	59,2	60,1	60,9
A-weighted	**91,5**	**92,7**	**94,0**	**95,4**	**96,8**	**97,6**	**98,5**	**99,5**	**100,5**	**101,5**

[*] A pantograph can also be treated as a point source – in the case $10*\log_{10}(165) = 22.2$ (dB) should be added to the tabular values.

3.4 Partial source contributions to HST pass-by noise

One typical example of partial source contributions to HST L_{AeqTp} at 300 km/h at the standard position 7.5m/1.2m found in [11] is shown in Fig. 3.7, and the corresponding ones based on the tuned SP acoustic source model is shown in Fig. 3.8. Compared, the SP tuned acoustic source model predicts the same noise level for wheel and aerodynamic components, 2.9 dBA lower for track contribution, and neglects the equipment noise (or merges it into aerodynamic noise – in this case the European example shall be 94 dBA for aerodynamic + equipment).

It is interesting to recall the example shown in Fig. 2.3 in Section 2.2, wherein rail/track contribution to L_{AeqTp} by the SP acoustic source model (before the tuning) is 1.1 dBA less than that by the supplier's source model. Together with the example showed here, it reminds us that example HST data, although may be representative, are still train-track dependent; they can differ from each other by a few dBA.

The source height is 0.01m above top of rail for rail/track noise and 0.5m above top of rail for equipment noise (the cooling fan noise). For the East Link, if assuming a 2m-high noise barrier will be built where necessary, pantograph noise will then become the most important source as shown in Fig. 3.9. In other words, the could-be error in predicting rail/track and equipment contribution to L_{AeqTp} is not important in this situation.

In Fig. 3.10 it is presented the noise emission data for the four partial sources, for a train speed 320 km/h. And, in Fig. 3.11, it is shown that the tuned SP source model works well in the whole frequency range. (For a comparison, see also Fig. 2.4.) Moreover, by this SP tuned source model aerodynamic noise becomes comparable to rolling noise at 320 km/h, reflecting a proper distribution of the noise sound power between the two noise types.

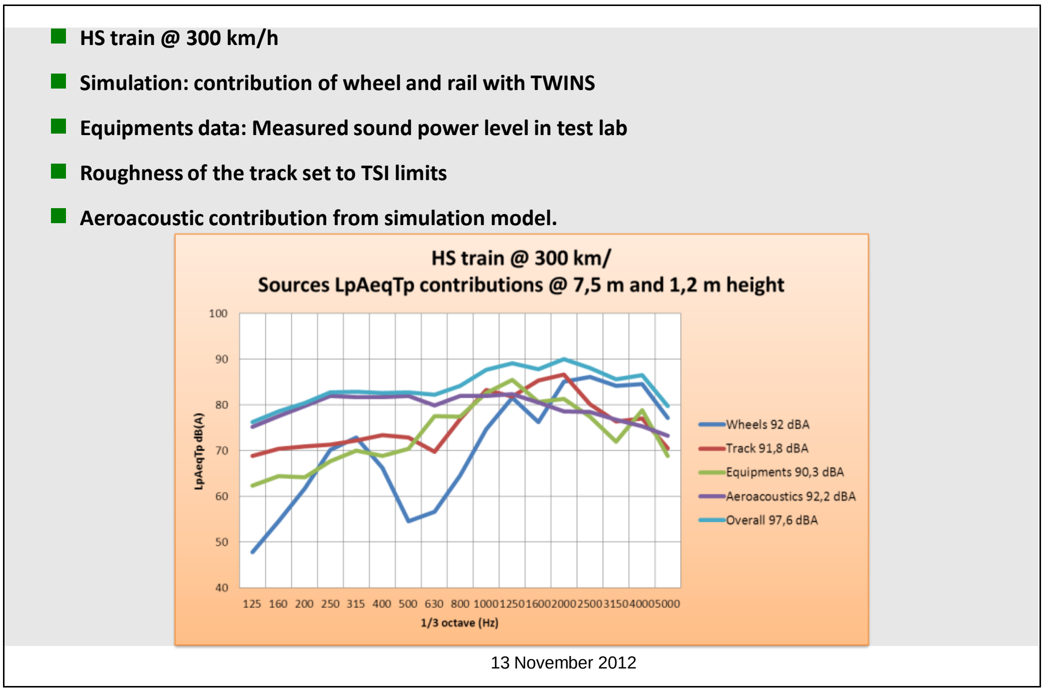


Fig. 3.7. *(Figure 7 in [11]): Example for wheel noise and rail noise at 300 km/h, Wheel =92dBA, Track 92 dBA, Equipment= 90 dBA, Aeroacoustics = 92 dBA, Total for all sources= 98 dBA.*

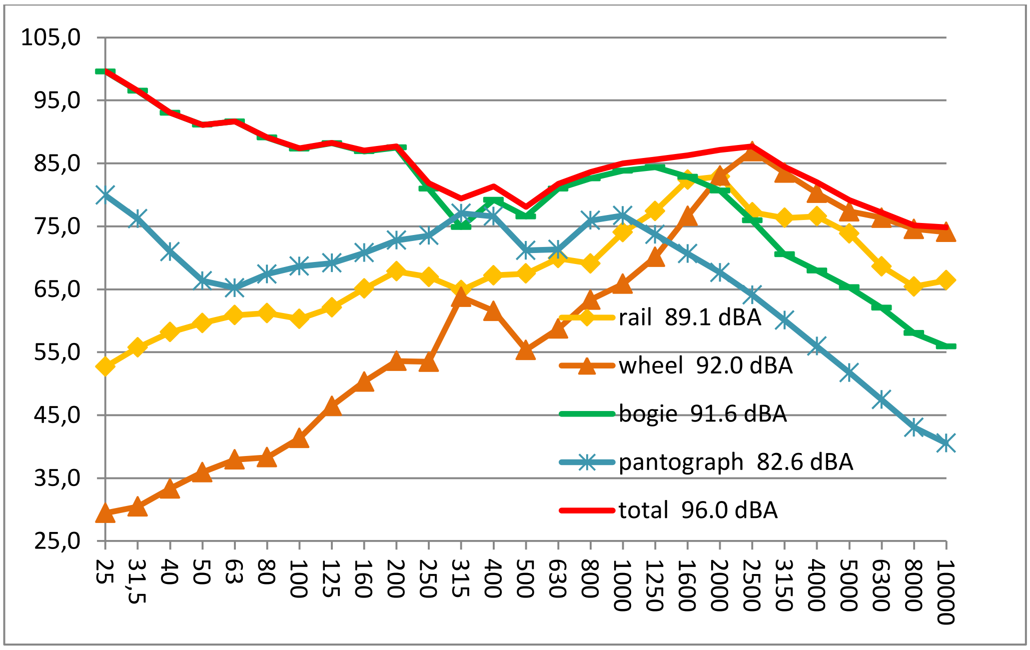


Fig. 3.8. *Similar as those in Fig. 3.7 while based on the tuned SP source model. Wheel = 92 dBA, Rail/track = 89 dBA, Aerodynamic = 92 dBA, Total for all sources = 96 dBA.*

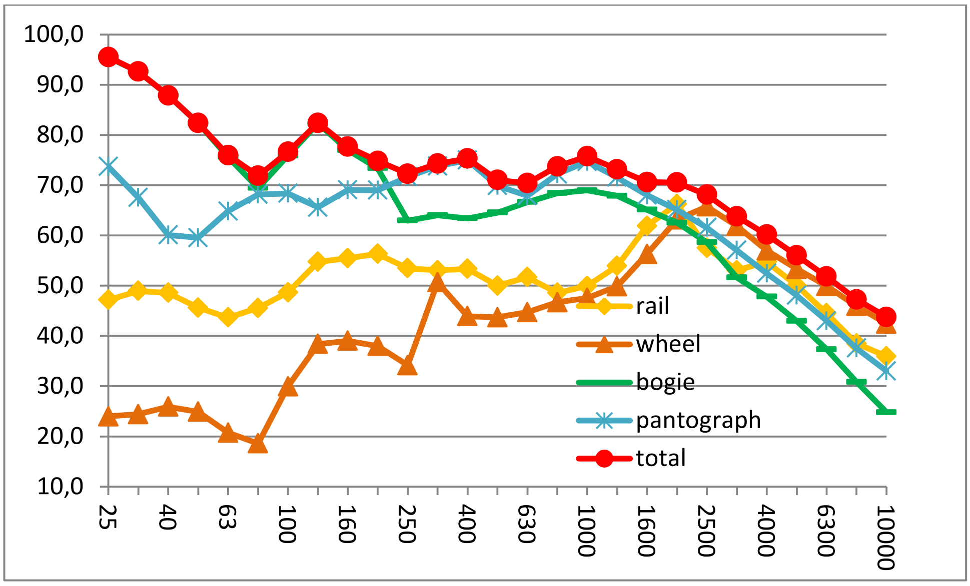


Fig. 3.9. *Partial source contributions to L_{AeqTp} at 320 km/h at 25m/3.5m position, with 2m high noise barrier located 5m from the track centre. The calculation is based on the tuned SP source model and sound propagation is handled by the Nord2000 model.*

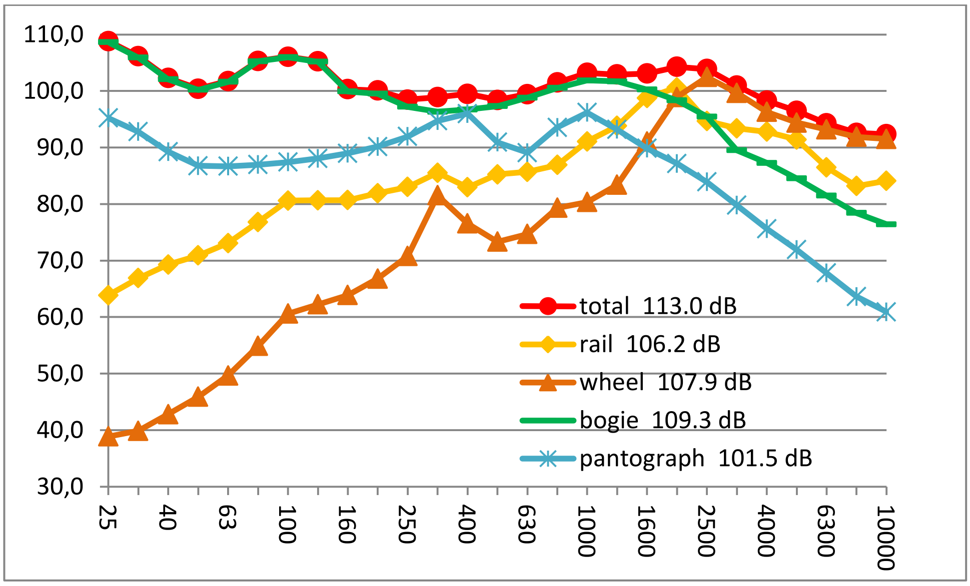


Fig. 3.10. *The tuned noise emission data for the four partial sources at 320 km/h.*

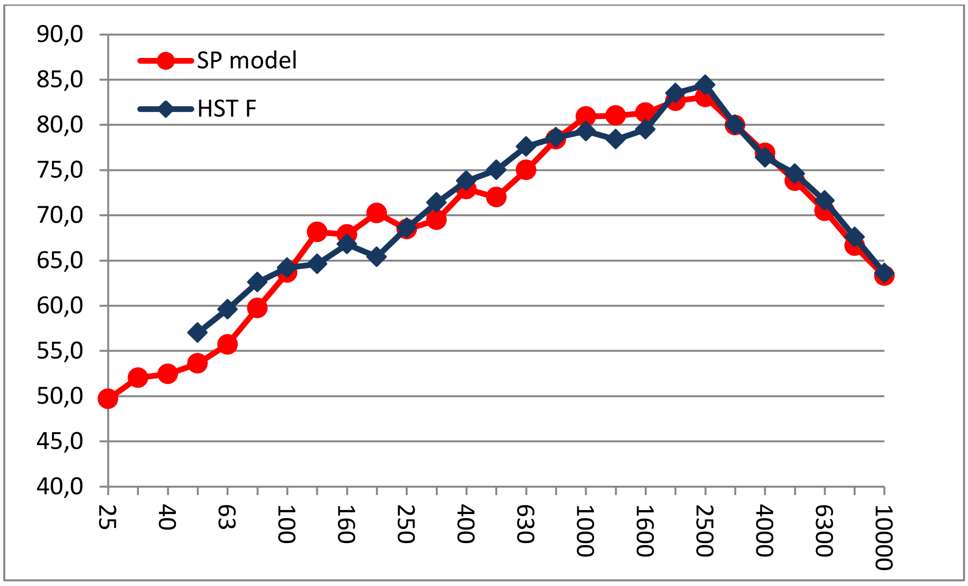


Fig. 3.11. *A comparison between the calculation of L_{AeqTp} using the tuned SP source data and one European representative HST pass-by data at 25m/3.5m position. (For comparison, see also Fig. 2.4.)*

3.5 Noise regulations in 2028

As has been discussed in Section 2.4, noise regulations are being revised regularly, by either lowering noise limit values, or improving test methods, or the both, following the technical process.

For reducing rolling noise, a list of existing noise measures is already quite long: rail dampers, rail web shields, wheel dampers, wheel skirts, sound absorption panels, near-track low barriers, new type of brakes (for freights), anti-curve-squeal measures, etc. For aerodynamic noise, it seems that noise measures that have been tested have also covered all the possibilities: streamline design, low-noise pantograph, pantograph insulation shield, bogie cover, inter-car cover, etc. Technically, after having applied some noise measures, a further noise reduction will become more difficult. Therefore it is important to make a smart design of noise measures [20].

Moreover, maglev trains do not need a pantograph. They are also free of rolling noise.

In the NOI TSI noise limit values are reduced from 1 up to 5 dB [11]. The future revision of the NOI TSI, e.g. in 2028, may reduce noise limit values further by 1 dB, while this reduction is not guaranteed. It depends on how many noise measures will have been effectively applied.

L_{AeqTp} values predicted by using the tuned SP acoustic source model are listed in the following:

- At a speed 80 km/h, 76.4 dBA at 7.5m/1.2m position and 77.2 dBA at 7.5m/3.5m position. The NOI TSI requirement is 80 dBA.
- At a speed 250 km/h, 92.8 dBA at 7.5m/1.2m position and 94.1 dBA at 7.5m/3.5m position. The NOI TSI requirement is 95 dBA.

These model prediction values indicate that if, in a future version of NOI TSI, noise limit values will further be reduced by 1 dB, the tuned SP acoustic source model does not need to be further adjusted.

4 Data dispersion

A good acoustic source model predicts noise impact level of a representative or mean value. As understood, a model prediction can differ from individual situations by some extent. Therefore, it is also important to specify the uncertainty and dispersion of the noise emission data for important partial sources.

4.1 Rolling noise and the ERATV database

One of specified tasks for Project 2 [5] is to study the ERATV (European Register of Authorised Types of Railway Vehicles) database [25]. In ref. [10], it was commented that "The database managed by ERA for TSI certified rolling stock contains very limit data and is not useful for the purpose to derive acoustic source models". However, this database is useful for studying the uncertainty and dispersion of rolling noise data of these TSI certified railway vehicles.

4.1.1 The ERATV database

The database was last updated on 29 May 2015. It is found that the total number of authorised vehicles which are registered is 178 and from 14 countries, of which only 119 contain noise data, as presented in Table 4.1. Relative sub-categories and the maximum design speeds are listed after the table.

Table 4.1. *The Member States and their ERATVs*

Country	Nr of ERATV	Nr of ERATV with pass-by noise data	Nr of ERATV for high speed (>= 250 km/h)
France	84	64	4 (320 km/h)
Poland	20	17	1 (250 km/h)
Italy	17	15	2 (300/250 km/h)
Latvia	17	0	0
United Kingdom	10	4	0
Lithuania	7	0	0
Czech Republic	6	5	0
Switzerland	5	3	1 (250/160 km/h)
Belgium	4	4	0
Luxembourg	2	2	0
Finland	2	2	0
Romania	2	1	0
Spain	1	1	1 (300 km/h)
Germany	1	1	0
Total:	**178**	**119**	**9**

9 subcategories presented in the ERATV:

1. Self-propelled passenger trainset (incl. railbusses)
2. Passenger Coach (incl. sleeping cars, restaurant, etc.)
3. Self-propelled special vehicle
4. Hauled special vehicle
5. Freight wagon
6. Locomotive
7. Shunter
8. Vehicle for services (e.g. kitchen)
9. Other (tramways, light rail vehicles, etc)

Maximum design speeds presented in the ERATV (in km/h):

50, 60, 80, 90, 100, 120, 130, 140, 160, 200, 220, 250, 300, 320, wherein 100, 120 and 160 are popular.

Relevant statistics information is presented in Table 4.2. Based on this information one can find the dispersion of the noise data as given below (for $L_{Aeq,Tp,\,80\,km/h}$):

- Self-propelled passenger trainset (incl. railbusses): 79.5 ± 1.5 dB (based on 47 data)
- Freight: 83 ± 2 dB (based on 25 data)
- Locomotive: 84.5 ± 1.5 dB (based on 34 data)

Table 4.2. *The distribution of pass-by noise levels. (Most, while not all, of the data are probably specified for* $L_{Aeq,Tp,\,80\,km/h}$*. Those data marked with yellow colour are likely specified at another speed as well as at another measurement position.)*

Vehicle subcategory	Max. design speed (km/h)	$L_{Aeq,Tp}$ (dBA)	Nr of ERATVs	Country
Self-propelled passenger trainset (incl. railbusses)	100	81	5	France
	120	74 81	1 1	France Poland
	130	80.7	1	Poland
	140	73	2	France
	160	78/79/80 76.4/79/79.5/79.8 74/78/79 81 78 74 80	2/8/8 1/1/1/1 2/3/2 2 1 2 1	France Poland Italy UK Czech Republic Switzerland Romania
	250	87 87	1 1	Poland Switzerland
	300	90 92	2 1	Italy Spain
	320	80/92	2/1	France
Passenger Coach (incl. sleeping cars, restaurant, etc.)	160	67	1	Poland
	200	80	1	Finland
Vehicle for services (e.g. kitchen)	200	80	1	Finland

Table 4.2. (continued)

Vehicle subcategory	Max. design speed (km/h)	$L_{Aeq,Tp}$ (dBA)	Nr of ERATVs	Country
Self-propelled special vehicle	100	85	1	Poland
Freight wagon	100	82/83/83.3/83.5/85 81 81/82 82	3/5/1/1/5 1 1/1 1	France Czech Republic Belgium Germany
	120	82.8/85 81 82 81	1/1 2 1 1	Poland UK Czech Republic Luxembourg
Locomotive	80	84	1	France
	90	85/86	1/1	Poland
	100	85 84/94.1 85/86 94	5 1/1 3/3 1	France Poland Italy Czech Republic
	120	84/85 85.7 85	6/5 1 1	France Poland Belgium
	140	83.5 83	3 1	France Belgium
	160	85	1	Poland
	220	85	1	Czech Republic
Other (tramways, light rail vehicles, etc)	100	79	1	Luxembourg

4.1.2 Other information

The noise data presented in [20] is also useful for estimating the dispersion of rolling noise, shown in Fig. 4.1 and 4.2 (in Fig. 4.2 a 2m high noise barrier is presented). Using the data below 250 km/h, one can estimate that the dispersion of rolling noise is about 1.5 ~ 2 dB(A).

And, the noise data showed in Fig. 4.4 presents a dispersion between 2 ~ 2.5 dB(A).

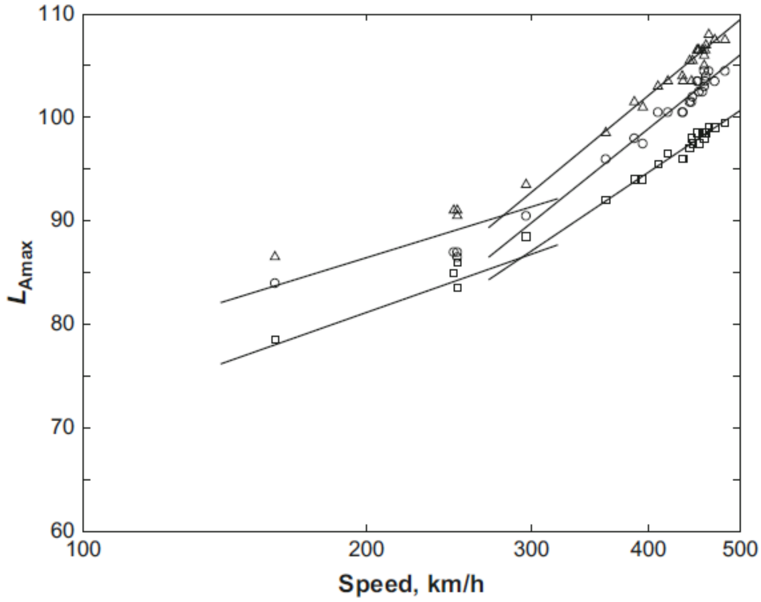


FIGURE 8-2 Maximum sound level of TGV-A at 25 m as a function of speed (data from [8.1]). △, leading power cars; ○, rear power cars; □, trailer vehicles

Fig. 4.1. *Noise data for several vehicle types [20].*

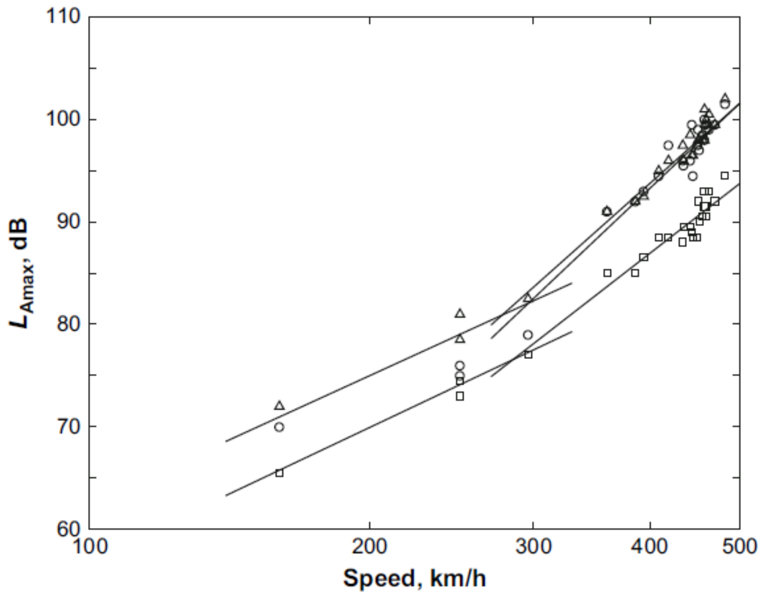


FIGURE 8-6 Maximum sound level of TGV-A at 25 m as a function of speed in the presence of a 2 m high barrier (data from [8.1]). △, leading power cars; ○, rear power cars; □, trailer vehicles

Fig. 4.2. *Noise data for several vehicle types (a 2m high noise barrier presented) [20].*

4.2 Aerodynamic noise

HST pass-by noise has been measured in numerous test campaigns. In public literature some useful information can be found for studying the dispersion of the noise data, as those given in [24, 26] and shown in Fig. 4.3 and 4.4.

As indicated in [24], the dispersion of external noise from different series of TGVs is around 1.5 dB(A) when measured at the same track. Different series of trains from different countries (TGV, ICE, ETR …) showed identical value at 300 km/h and up to 2 dB(A) at 250 km/h.

In Fig. 4.4 it shows that the dispersion for the ICE data is larger than for the TGV data.

Pass-by noise values measured at 25m in dB(A)	**Test site**	**Train speed (kph)**			
TSI+ tracks except Belgium		**250**	**300**	**320**	**350**
TGV Thalys	Belgium	88.5	92	93	
	France	85.5	90	92	
	Germany	85.5			
TGV Duplex	France	87	91	92	95
TGV Atlantique	France		90.5		94.7
TGV Réseau	France	89	91.5	94 (330kph)	97
ICE3	France	87.5	90	91.5	
	Germany	85.5	89	92	
AVE	Spain	86	90	91	
ETR480	Italy	90.5			
ETR500	Italy	88	90.5		
TSI limits	*TSI+*	-	*92*	*94*	-

Tab. 1 : pass-by noise values of high speed trains measured at 25m

Fig. 4.3. *HST pass-by noise of different train types measured at the same site at 25m distance [24].*

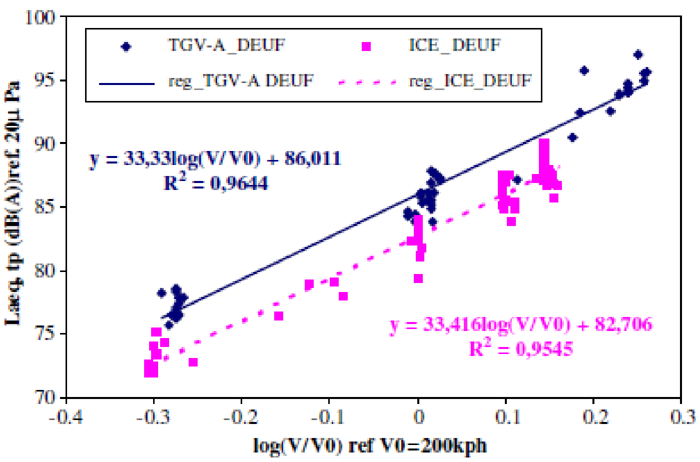


Fig. 9. Linear curve fitting of data measured in the DEUFRAKO project.

Fig. 4.4. *Pass-by noise measured in the DEUFRAKO project [26]. (For $\log_{10}$ (V/200), it becomes - 0.3 for V=100, - 0.1 for V=158, 0.1 for V=250 and 0.3 for V=400.)*

4.3 Pantograph noise

One example for pantograph noise dispersion was found in [27], presented in Fig. 4.5. The dispersion is about 2.8 dB for Series E2, and 1.5 dB for FASTECH360S.

It should be noticed that low noise pantographs have been studied and developed in Japan for many years. Pantographs for Japanese Shinkansen 700 series is about 12 dB quieter than those of Japanese Shinkansen 300 series.

Pantographs in Europe have been also much improved acoustically, which can be seen by the changes in their exterior. However, unfortunately, noise data of pantographs of European designs is still not available in the public.

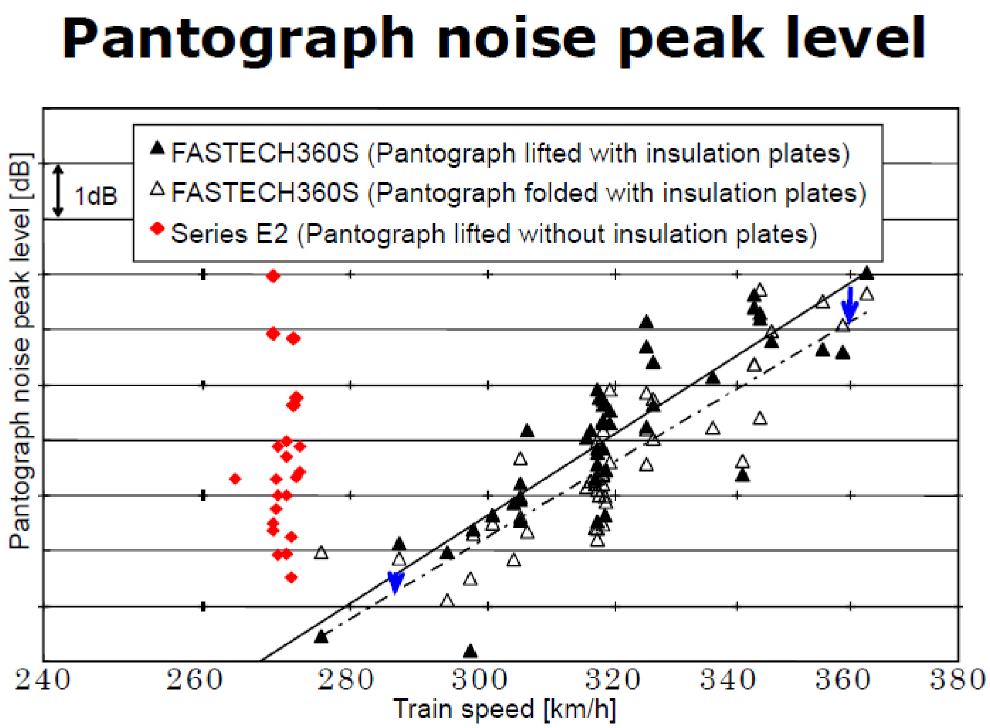


Fig. 4.5. *Dispersion of pantograph noise [27].*

.

5 Conclusion remarks

To properly prepare noise emission data for a future HST is a challenge task. It is considered too risky if taking all the quietest designs in the world and today because some of them may not appear in European market even by 2028. However, a conservative proposal is also not practically acceptable because consequent noise measures will be too expensive. A proper proposal of the noise emission data should be based on today's European designs as well as the best available in European market.

The output of Project 1 [10] provides some solid references. Together with the discussions made in Chapter 2 in this report, it is concluded that it is probable and then accepted to reduce pantograph noise by 1.5 dB. Thus, in total, pantograph noise was reduced by 7.5 dB when shifting from X2 trains to HSTs.

In Japan, low-noise pantographs are extremely important because along Japanese railway lines it is often densely populated. If the pantograph noise for X2 trains is comparable to that of Japanese Shinkansen 300 series, then technically a new type of pantographs can be made up to 12 dB quieter. However, it is considered too risky at this time to propose such a large noise reduction for pantograph noise, because such a quiet pantograph may not be available in European market even by 2028.

For rolling noise, the noise emission data was reduced by 8 dB when shifting from X2 trains to HST trains. And, a further 2.5 dB reduction is made at 3150 Hz by referring to the representative HST pass-by noise data.

Separation of rolling noise components follows the track and vehicle transfer functions. The CONOSSOS-EU track and vehicle transfer functions have been referred to when making the separation. However, if some noise measures (e.g. rail/wheel dampers, rail web screen, wheel skirts, etc) will have been applied on future HSTs, these transfer functions can vary even a lot. In the case the respective noise emission data should be revised.

The spectrum data of pantograph noise given in the SP acoustic model is estimated. It can suffer revision when pantograph noise of future HSTs will have been collected.

Above 5000 Hz, a quite big difference was found between noise predictions using the (former) SP acoustic source model and the representative European HST pass-by noise data, shown in Fig. 2.2 and Fig. 2.4. It may suggest that 8 dB reduction in noise emission data for rolling noise should not be (fully) applied on these high frequency components when shifting from X2 trains to HSTs. The could-be reasons are: (1) By the contact filter effect it implies that a change in roughness level at very short wavelengths is much less sensitive than at long wavelengths. (2) Rail dampers usually work below 1600 Hz and wheel dampers are usually tuned around 2500 Hz then they are likely being less effective above 5000 Hz. (3) Acoustic rail grinding may not be effective at short wavelengths. While, at this moment it is not certain to provide an explanation so it is decided to simply follow the representative European HST noise data. Thus, the noise emission data for rolling noise is revised in a way: - 8 dB for $f \leq 5000$ Hz, - 0 at 10 000 Hz, and a smooth transition in the between, when shifting from X2 trains to HSTs.

Similarly, from 250 Hz and below where aerodynamic noise dominates, the comparison also showed a big difference. As in the SP acoustic source model, for this low frequency range, the non-pantograph components of aerodynamic noise were modelled by a monopole source. This monopole source originates from the pressure rise caused by the outward-pushed air (from the track) when a train approaches, and the pressure drop caused by the inward-dragged air when the train recedes. The noise emission data for this monopole source should not be reduced when shifting from X2 trains to HSTs because they have a similar cross section area. Accordingly, a revision is made in the way: - 6 dB for f $\geq$ 315 Hz, - 3 dB at 250 Hz, and no reduction for f $\leq$ 200 Hz, when shifting from X2 trains to HSTs.

The spectrum data of pantograph noise below 200 Hz was further revised by deleting the resonance, referring to several pantograph noise data found in literature.

Comparisons made in Fig. 2.2 and Fig. 2.4 showed that in the important frequency range the former SP acoustic source model works quite well when no barrier presented. After the tuning, the SP acoustic source model works well in the whole frequency range (Fig. 3.11), also well when a noise barrier presented (comparing Fig. 3.7 and Fig. 3.8). Moreover, as mentioned in Section 2.3, the tuned SP acoustic source model will predict a barrier insertion loss 9.5 dB, compared to the example given in [20] wherein barrier insertion loss is about 10.5 dB.

With the tuned SP source data, rolling noise and aerodynamic noise become comparable at 320 km/h, which reflects a proper estimation of the sound power levels of the two noise types. In other words, 8 dB reduction on rolling noise and 6 dB reduction on aerodynamic noise are the two proper estimations (when shifting from X2 trains to HSTs).

Although the acoustic source model may suffer further revisions in future especially when HST noise data will have been collected in Sweden, the 1.5 dB reduction in pantograph noise emission data, as well as revisions below 315 Hz and above 5000 Hz, is a big improvement in the acoustic source modelling.

If in a future version of NOI TSI noise limit values will further be reduced by 1 dB, the tuned SP acoustic source model does not need to be further adjusted.

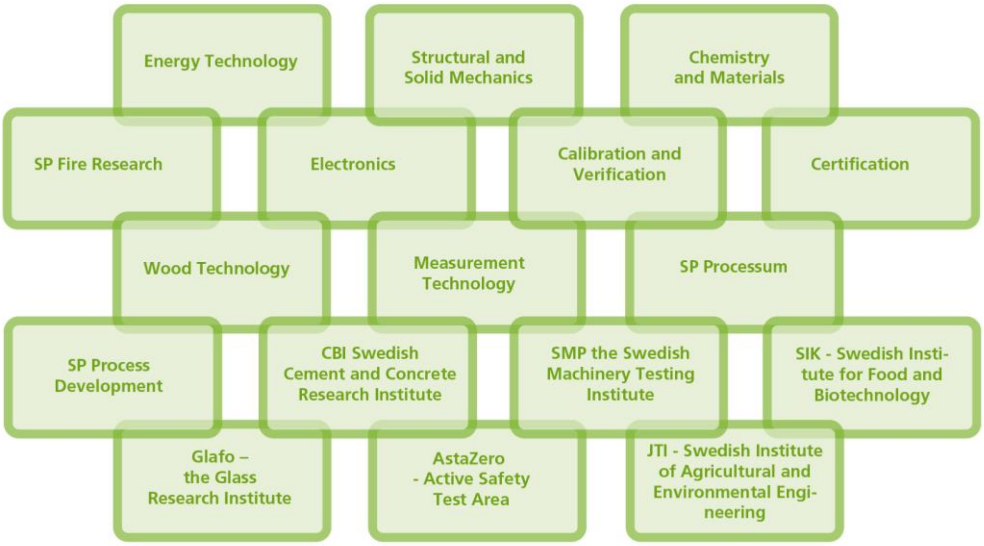
Reference

[1] Jorgen Kragh, Birger Plovsing, Svein Å. Storeheier and Hans G. Jonasson, Nordic Environment Noise Prediction Methods, Nord2000 Summary Report, General Nordic Sound Propagation Model and Applications in Source-Related Prediction Methods, AV 1719/01, DELTA, 31 May 2002.
[2] Birger Plovsing, Nord2000. Comprehensive Outdoor Sound Propagation Model. Part 1: Propagation in an Atmosphere without Significant Refraction, AV 1849/00, Noise & Vibration, DELTA, 31 March 2006.
[3] Birger Plovsing, Nord2000. Comprehensive Outdoor Sound Propagation Model. Part 2: Propagation in an Atmosphere with Refraction, AV 1851/00, Noise & Vibration, DELTA, 31 March 2006.
[4] Birger Plovsing, Changes in the Nord2000 propagation model since year 2001, Technical Note, AV 1307/05, Noise & Vibration, DELTA, 31 March 2006.
[5] Kjell Strömmer, Uppdragsbeskrivning: Ljudnivådata för tåg i trafik 2028, utkast 3, 2015-07-06.
[6] Xuetao Zhang, Prediction of high-speed train noise on Swedish tracks, SP Report 2010:75.
[7] Xuetao Zhang, Noise Assessment Method for High-Speed Railway Applications in Sweden, SP Report 2014:34 Rev.
[8] DIRECTIVE 96/48/EC — INTEROPERABILITY OF THE TRANS-EUROPEAN HIGH SPEED RAIL SYSTEM, TECHNICAL SPECIFICATION FOR INTEROPERABI-LITY, ‘Rolling stock’ Sub-System, 26 March 2008.
[9] Commission Regulation (EU) No 1304/2014 of 26 November 2014: on the technical specification for interoperability relating to the subsystem ‘rolling stock – noise’ amending Decision 2008/232/EC and repealing Decision 2011/229/EU.
[10] Anders Frid, Assessment of an acoustic source model for high speed trains, ÅF Rapport 6068065-01, 2015-07-03.
[11] Oscar Martos, Andreas Schirmer and Ernest Godward, NOISE TSI – Final Report, INTEROPRRABILITY UNIT, 15/01/2014.
[12] Common Noise Assessment Methods in Europe (CNOSSOS-EU), JRC72550, European Union, 2012. ISBN 978-92-79-25281-5 (pdf); ISSN 1831-9424 (online).
[13] F.G. de Beer, M.H.A. Janssens, and M.G. Dittrich, Indirect Roughness Measurement (MetaRail Task III.3, Deliverable 8), June 1998.
[14] F.G. de Beer, H.W. Jansen, and M.G. Dittrich, STAIRRS Level 2 measurement methods: Indirect roughness and transfer function, 15 July 2002.
[15] Communication with my colleague Håkan Andersson (SP).
[16] D.J. Thompson, C.J.C. Jones. Study on the sensitivity of the indirect roughness method to variations in track and wheel parameters (STAIRRS report) ISVR Contract Report 01/xx, April 2001.
[17] D.J. Thompson, M.H.A. Janssens, F.G. de Beer. TWINS Track-Wheel Interaction Noise Software, Theoretical manual (version 3.0) (Silent Freight/Silent Track Report) TNO-report HAG-RPT-9900211, November 1999.
[18] prEN 15461:2005 (E), Railway applications – Noise emission – Characterisation of the dynamic properties of track sections for pass by noise measurements.
[19] Xuetao Zhang, Applying the TSI formulae together with the multiple-interpolations method to determine track decay rates using train pass-by measurements (in06_55), Inter-Noise 2006, 3-6 December 2006, Honolulu, Hawaii, USA.
[20] David Thompson, Railway Noise and Vibration: Mechanisms, Modelling and Means of Control, Elsevier 2009.
[21] Xuetao Zhang, Empirically modelling railway aerodynamic noise using one microphone pass-by recordings, (accepted to be published in) Notes on Numerical Fluid Mechanics and Multidisciplinary Design (2014).
[22] Private communication with Takehisa Takaishi at Japanese Railway Technical Research Institute, October 2010.
[23] C. Charbonnel, Definition of a simple model of sources for the TGV-R, HAR12TR-021206-SNCF01 (the Harmonoise technical report).
[24] F. Poisson, P.E. Gautier, F. Letourneaux, Noise sources for high speed trains: a review of results in the TGV case, the 9th International Workshop on Railway Noise, Munich, Germany, September 4-8, 2007.

[25] https://eratv.era.europa.eu/eratv/
[26] C. Mellet, F. Létourneaux, F. Poisson, C. Talotte, High speed train noise emission: Latest investigation of the aerodynamic/rolling noise contribution, *Journal of Sound and Vibration 293* (2006) 535–546.
[27] Takao Nishiyama, Japanese Vision on High Speed and the Environment, 2011 International Practicum on Implementing High-Speed Rail in the United States, 4 May 2011.

SP Technical Research Institute of Sweden

Our work is concentrated on innovation and the development of value-adding technology. Using Sweden's most extensive and advanced resources for technical evaluation, measurement technology, research and development, we make an important contribution to the competitiveness and sustainable development of industry. Research is carried out in close conjunction with universities and institutes of technology, to the benefit of a customer base of about 10000 organisations, ranging from start-up companies developing new technologies or new ideas to international groups.



SP Technical Research Institute of Sweden
Box 857, SE-501 15 Borås, SWEDEN
Telephone: +46 10 516 50 00, Telefax: +46 33 13 55 02
E-mail: info@sp.se
www.sp.se

Sustainable Built Environment
SP Report 2015:42
ISSN 0284-5172

More information about publications published by SP: **www.sp.se/publ**