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**Noise emission of European railway cars
and their noise reduction potential:
data collection, evaluation and
examples of Best-Practice railway cars**

Summary

by

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UMWELTBUNDESAMT

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1 Introduction

For the harmonisation of European rail traffic and also for a reduction of rail traffic noise the Technical Specifications for Interoperability (TSI), the TSI High Speed Rail System:2002 [1] (revised TSI High Speed Rail System:2008 [3]) and the TSI Noise:2006 [2] (revised TSI Noise:2011 [4]) were introduced. For the first time, these regulations determine uniform Europe-wide noise limit values for the homologation of new trains as well as for rebuilt or modernized vehicles thus contributing actively to protection against noise pollution.

Figure 1 gives an overview on the acoustic requirements of the TSI. The interior noise in the driver's cab is not considered in the further context of this investigation.

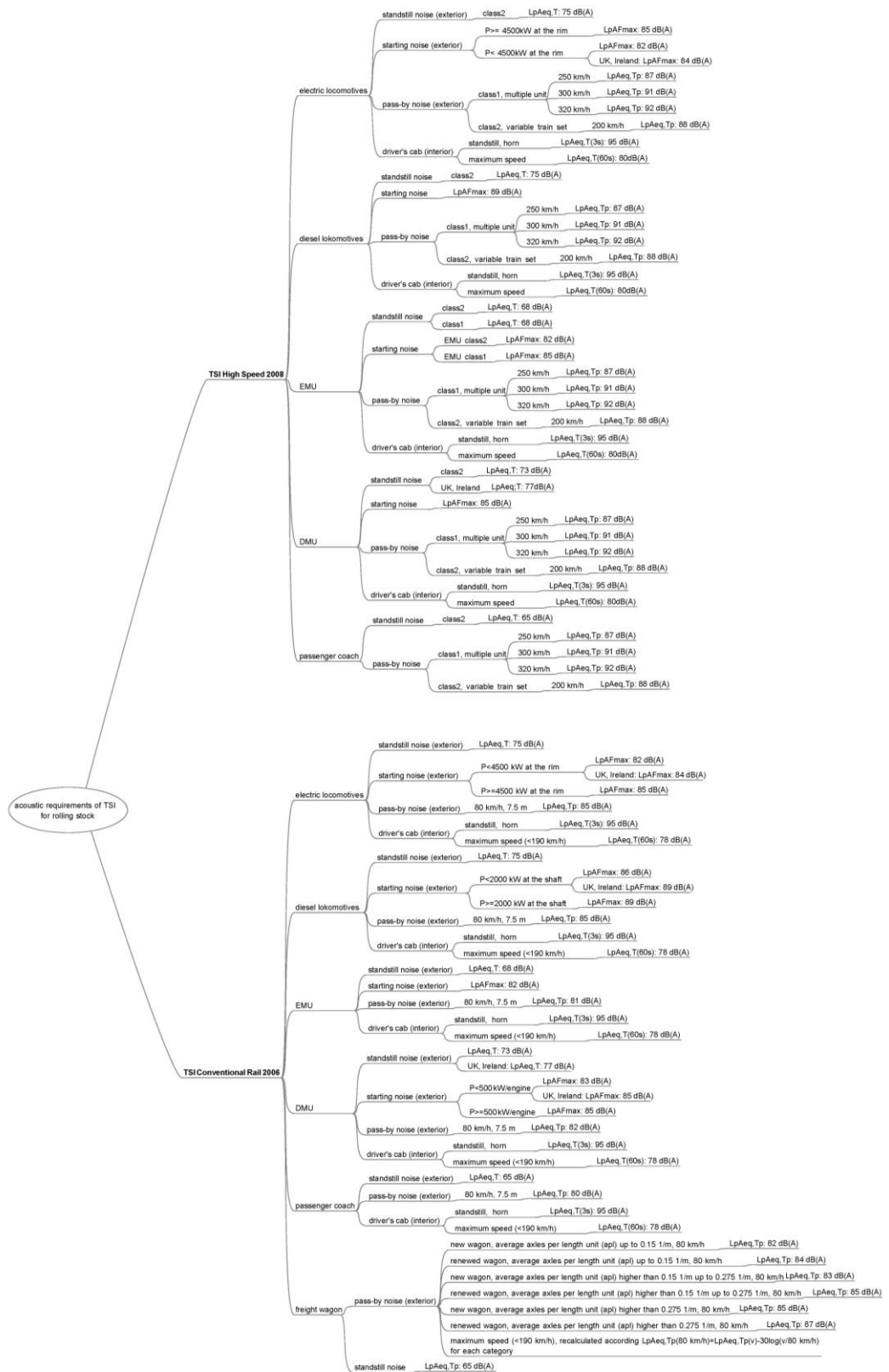


Figure 1. Overview on all acoustic requirements of the TSI.

Still the population's exposure to rail traffic noise is a serious environmental problem, particularly at so-called hot spots as e.g. the Rhine Valley in Germany. Otherwise, so environment-friendly rail traffic noise has its Achilles' heel in rail traffic noise. But the railway is competing with other modes of transport, such as carriage by road or air. Significant additional costs occurring only for the railway sector weaken the competitiveness of railway systems and do not consequently lead to a reduced environmental pollution.

There is a number of arguments both for and against the reduction of limit values. But on the whole, it remains an undisputed fact that in particular noisy vehicles, which are not in compliance with the state-of-the-art, are responsible for an excessive exposure of environment and population to noise. For noise mitigation the noise emitted from railway vehicles should therefore be reduced according to the state-of-the-art. This guarantees that:

- the noisiest vehicles, which are not in compliance with the state-of-the-art, will not any longer pass the homologation tests and will disappear from the market by and by,
- the new limit values can be achieved technically (orientation to the state-of-the-art),
- the new limit values can be realised also under competitive conditions.

The present research project deals with the determination of the state-of-the-art for noise emissions from European railway vehicles. Noise emission data were collected and evaluated and the noise mitigation potentials were determined. Best practice vehicles show that significant improvements in noise reduction are possible.

2 Mechanisms of noise generation and of noise mitigation

Noise emissions from railway vehicles can be divided into rolling noise (relevant for pass-by noise) and aggregate noise (relevant for stationary noise and starting noise).

Additionally, aerodynamic noise might be relevant for high velocities ($v > 300$ km/h). For rolling noise, the complex interaction between wheel and track with its superstructure is of importance. The roughness of the wheel's running surface and the track surface cause vibrations of the wheels and the track. The magnitude of the vibrations here depends on the mechanic properties of both systems. Dynamic stiffnesses of the subsystems (e.g. impedances) and their damping have a great influence. Finally, the vibrations are radiated as noise.

The following figure shows the most important mechanisms.

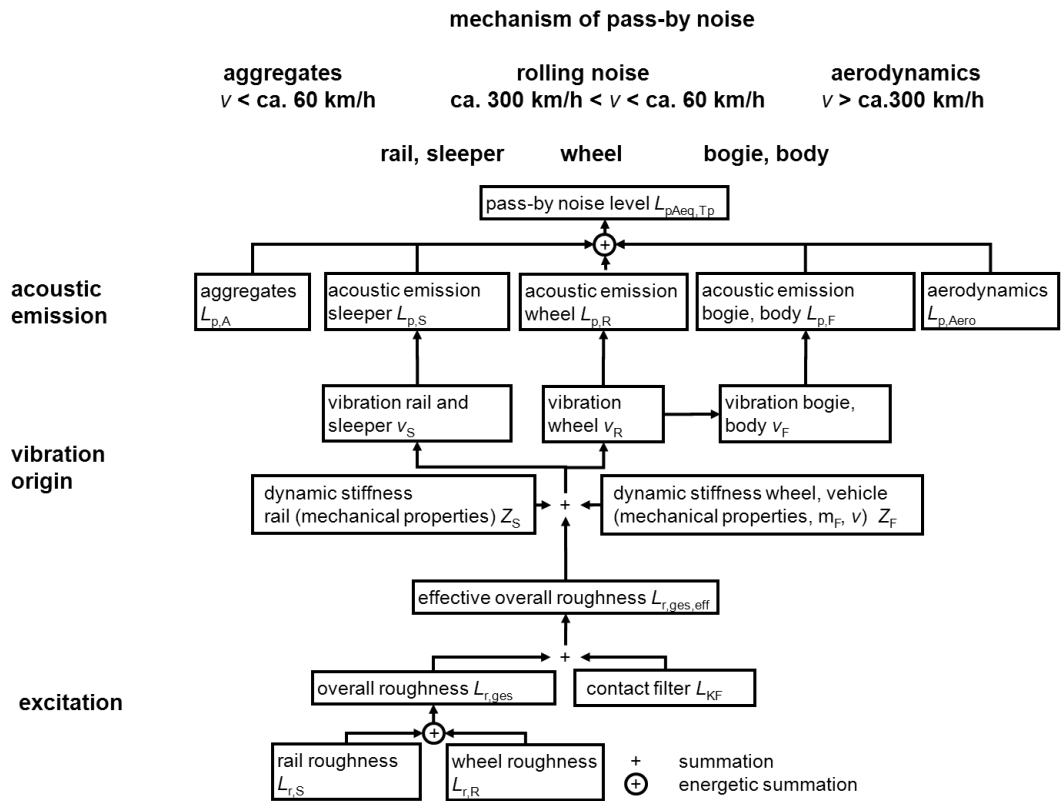


Figure 2. Model for the calculation of pass-by noise (logarithmic values).

The distribution of noise radiation to the subsystems wheel and track depends on the construction of wheel and track, often the noise radiated by wheel and track is approximately the same. Regarding the effectiveness of mitigation measures, which usually influence only a subsystem, this means that there is only a limited effect.

Potential reduction measures are registered in the following figure.

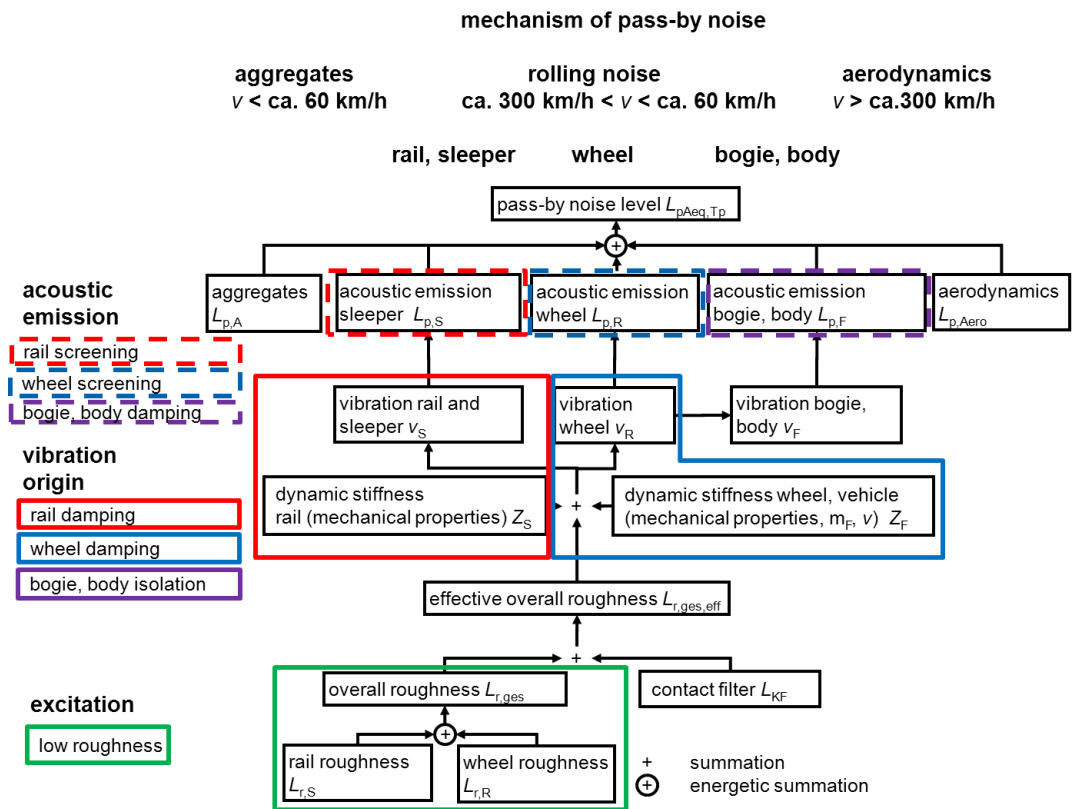


Figure 3. Reduction measures for pass-by noise (logarithmic values).

For assessing the effectiveness of noise mitigation measures literature was reviewed regarding research projects and practice-based projects. In order to guarantee comparable conditions for the TSI measurements attention was paid to ensure that the tests were carried out at reference tracks or, at least, that the wheel roughness and decay rates are recorded and taken into account when analysing the data.

The measured noise reduction of a noise reduction product will depend on the wheel and track contributions (depending e.g. on the stiffness of the intermediate layer, temperature, if applicable, construction of the superstructure, vehicle type, and so on) to the total noise emissions. The noise mitigation effect might be different at another position or for another railway vehicle. Most of the investigations carried out, however, lead to comparable results.

Furthermore, only results for sound reduction systems that have been tested under operation conditions shall be indicated.

As a consequence, such areas shall be listed, in which the mitigation measures are typically found due to the situative and product-dependent results.

Table 1. Mitigation effect of noise reduction measures for pass-by noise.

	Improvement in total noise emissions in dB for high speed traffic	Improvement in total noise emissions in dB for freight wagons
Optimisation of the wheel geometry	1 – 2	0 – 1
Wheel noise absorber	1 – 5	1 – 2
Constrained layer	4 – 5	-- ¹
Bogie skirts	--	1 – 2

A reduction of the rolling noise for conventional railway vehicles can in practice be achieved by proven technologies. The achievable noise reductions lie in sum between 2 dB and 5 dB.

Other than for rolling noise the noise emissions of the vehicle aggregates have dominating effects at standstill and when starting.

In the following figure exemplarily relevant noise sources for the coach NDW are shown:

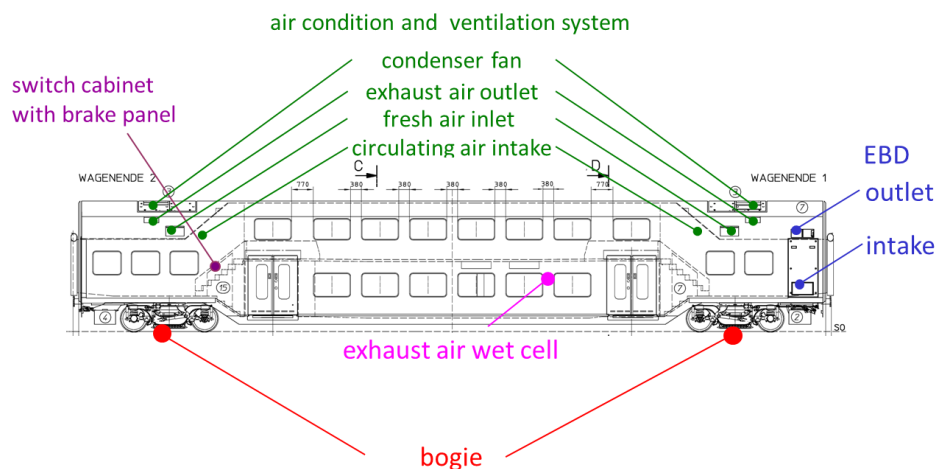


Figure 4. Noise sources at the low-floor double-decker rail coach (NDW) [13].

Depending on vehicle type and operation condition (stationary or starting) different vehicle aggregates might be relevant for noise emission. The noise emission of aggregates may be reduced significantly by measures developed within the scope of an acoustical management, which generally starts in the early phase of design and from there on supports the whole process of the project ([14], [15]). For this numerous validated measures exist.

¹ Not applicable for block-braked vehicles due to the high braking temperature of the wheel.

The stationary noise and the starting noise of railway vehicles can be significantly reduced with practicable concepts. The great number of quiet vehicles available in the market can illustrate this.

3 Data base

Key issue of the project was the preparation of a well-founded data base for the state-of-the-art of noise emission (exterior noise) from European railway vehicles. In this context, values from acoustic type tests of newly homologated railway vehicles, collected on the basis of the TSI Noise 2006 and the TSI Noise 2011, were collected.

First, a comparative assessment of the measuring and operation conditions of both TSI Noise versions is necessary in order to judge, whether the data collected on the basis of the TSI Noise 2011 can be deemed to be comparable. For this purpose, both TSI guidelines were compared with regard to measuring quantities, measuring conditions, operation conditions of the vehicle and track requirements.

The comparison shows that the values measured according to both TSI guidelines can to a great extent be considered comparable. As for stationary noise, however, the changes in the measuring and operation conditions must be taken into account, in particular for electrical multiple units (EMU) and passenger trains (operation of the air-conditioning compressor required in TSI Noise 2011, but not in TSI Noise 2006).

A large number of acoustic limit values for railway vehicles are listed in the TSI. The limit values are given in the respective specifications:

- TSI Noise Conventional Rail System
- TSI High Speed Rail System

for the individual railway vehicle categories

- electric locomotives,
- diesel locomotives,
- electrical multiple units,
- diesel multiple units,
- coaches and
- freight wagons.

Partly, a distinction should be made regarding different vehicle-specific parameters (e.g. power at the shaft).

Besides there is a distinction between the operation modes

- stationary,
- starting and
- pass-by at different driving speeds.

Basic ideas for the elaboration of the questionnaires were:

- clarity,
- simple completion,
- clear questions.

Both for keeping the questionnaires simple and clear and in order to keep the number of questionnaires within reasonable limits individual questionnaires for each category of railway vehicles have been set up. These questionnaires ask for the railway-specific parameters. The acoustic characteristics as determined in the type tests could be entered.

In addition to the vehicle data details on rail roughness and the decay rate were collected.

The data collection itself has been carried out within the homologation process for various parties:

- manufacturers of railway vehicles,
- railway vehicles operating companies,
- notified bodies,
- measuring institutes.

The response rate of the survey was very good overall. Representative data could be gathered.

To ensure confidentiality only anonymous data collection was possible for most of the participants.

Prior to recording the values collected in acoustic type tests in a data base several checks were performed to in order to guarantee a high quality of the stored data:

1. Check of datasets with regard to duplicate files. As far as duplication was assumed the dataset was not added to the data base.
2. Partly, mean or maximum values were transferred for a number of vehicles. As an allocation to particular vehicles was not possible these data were not considered.

3. In data collection special emphasis was laid on the compliance with the reference track properties of the test track. The collected data of the pass-by measurements were classified in two categories in terms of their availability:
 - If compliance with the track conditions (rail roughness and decay rate) can be assumed the data of the pass-by measurement will be deemed to be trustworthy (assurance class I).
 - If measurement results for rail roughness and decay rate are not available or if the specific limit values are not kept the data are considered to be comparable only to a limited degree (assurance class II).

For assessing the pass-by measurements only data of assurance class I are considered.

4. Furthermore the data were checked for plausibility:
 - With plausibility checks in the questionnaires it was possible to identify contradictory or false (where recognisable) information in the questionnaires.
 - The collected data were compared with values from type tests conducted by Müller-BBM.

In the event of any doubt as for plausibility the data were not considered in the evaluation.

5. The remaining data were grouped by sources (notified bodies, manufacturer, operator) and the individual results were compared to each other (mean value and standard deviation). Thus, it could be guaranteed that no filtered data (particularly quiet or noisy vehicles) were passed on with the forwarding of data from the individual sources.

The collected data nearly exclusively originate from type tests according to the TSI Noise 2006. The effects of modified measuring and operating conditions were evaluated. Pass-by measurement data as recorded in compliance with the TSI Noise 2011 were only used when the pass-by measurements were classified as comparable in terms of the TSI Noise 2011.

As far as the data showed significant differences for individual construction types (e.g. diesel-electric and diesel-hydraulic engines) this was considered in the evaluation so that no technology is foreclosed from the market.

The result of the data collection is listed in the following table:

Table 2. Results of the data collection for the operating conditions and railway vehicle categoris of the TSI Noise.

category	noise	TSI limit dB(A)	average dB(A)	standard-deviation dB	average of the most quiet 33 %	median dB(A)	lower quartile dB(A)	upper quartile dB(A)	number of data (overall 378)
diesel locomotives	standstill noise	75	68.1	2.8	64.7	69.0	65.5	70.5	33
	starting noise P _≥ 2000 kW	89	82.7	3.3	79.5	82.5	81.0	84.0	16
	starting noise P<2000 kW	86	83.4	2.1	81.2	84.0	82.5	85.0	18
	pass-by noise 80 km/h	85	83.7	1.5	81.9	84.0	82.5	85.0	21
electric locomotives	standstill noise	75	62.2	4.3	57.8	61.0	57.8	66.3	12
	starting noise P _≥ 4500 kW	85	81.9	1.2	80.7	82.0	81.0	82.5	9
	starting noise P<4500 kW	82	80.3	0.6	80.0	80.0	-	-	3
	pass-by noise 80 km/h	85	83.5	1.4	82.3	84.0	82.5	84.3	10
EMU	standstill noise	68	55.4	5.0	50.5	55.0	52.0	59.0	33
	starting noise	82	73.8	3.2	70.9	72.0	71.0	76.5	33
	pass-by noise 80 km/h	81	76.2	1.4	74.9	76.0	75.0	77.0	24
DMU	standstill noise	73	66.9	4.0	62.4	68.5	63.0	70.0	14
	starting noise P _≥ 500 kW	85	79.4	3.3	77.0	77.0	77.0	83.0	5
	starting noise P<500 kW	83	81.1	2.1	78.7	82.0	79.5	83.0	9
	pass-by noise 80 km/h	82	78.9	2.4	77.0	79.0	78.0	80.5	10
passenger coaches	standstill noise	65	60.1	4.7	57.0	62.0	59.0	63.0	7
	pass-by noise 80 km/h	80	76.8	0.8	76.0	77.0	76.0	77.5	5
freight wagons	standstill noise	65	-	-	-	-	-	-	0
	new wagons, apl up to 0.15 1/m, 80 km/h	82	78.2	2.8	75.5	78.5	76.8	80.3	6
	new wagons, apl higher than 0.15 1/m up to 0.275 1/m, 80 km/h	83	80.1	2.4	77.5	80.0	78.0	82.0	43
	new wagons, apl higher than 0.275 1/m, 80 km/h	85	80.9	2.8	77.6	81.5	78.3	83.0	32
	renew ed wagons, apl up to 0.15 1/m, 80 km/h	84	83.0	-	-	-	-	-	1
	renew ed wagons, apl higher than 0.15 1/m up to 0.275 1/m, 80 km/h	85	-	-	-	-	-	-	0
	renew ed wagons, apl higher than 0.275 1/m, 80 km/h	87	-	-	-	-	-	-	0
	renew ed wagons, apl bis 0.15 1/m, 190 km/h recalculated 80 km/h	82	80.0	0.0	80.0	-	-	-	2
	new wagons, apl higher than 0.15 1/m up to 0.275 1/m, 190 km/h recalculated 80 km/h	83	81.9	1.1	81.0	82.0	81.8	83.0	14
	new wagons, apl higher than 0.275 1/m, 190 km/h recalculated 80 km/h	85	81.7	2.9	78.7	83.0	80.0	83.5	17
	renew ed wagons, apl higher than 0.15 1/m, 190 km/h recalculated 80 km/h	84	83.0	-	-	-	-	-	1
	renew ed wagons, apl higher than 0.15 1/m up to 0.275 1/m, 190 km/h recalculated 80 km/h	85	-	-	-	-	-	-	0
	renew ed wagons, apl higher than 0.275 1/m, 190 km/h recalculated 80 km/h	87	-	-	-	-	-	-	0

There is a strong scatter of the results for stationary and starting noise. Partly, the emission parameters of the railway vehicles are clearly below the limit values. The scatter of results for pass-by noise is at a significantly lower level. Only for freights wagons larger scatters can be observed. All pass-by levels are clearly closer to the existing limit values than the stationary and starting noise values.

4 Determination of the state-of-the-art

According to the ISO 11689 [9] the low noise-control performance level L_1 (high noise-emission machines) and the high noise-control performance level L_2 (low noise-emission machines) are determined.

- High noise-emission machines (low acoustic level):
 L_1 is the highest integer value achieved or exceeded by the noisiest 17.5 % of the investigated vehicles.
- Low noise-emission machines (high acoustic level):
 L_2 is the smallest integer value that the quietest 10 % of the investigated railway vehicles achieve or fall below.

Based on the collected data the state-of-the-art was determined as follows and according to the ISO 11689 and the DIN EN ISO 12100.

A machine is in compliance with the state-of-the-art when its noise emission value is below that of 50 % – 75 % of the other machines in its group.

Two values are defined for the state-of-the-art:

- Moderate state-of-the-art:
Median of noise emission data.
- Ambitious state-of-the-art:
Lower quantile of noise emission data.

With this methodology noise emissions are determined that comply with the state-of-the-art.

On this basis limit values are proposed. Two stages of limit values are defined:

- A first stage of limit values which can be achieved by the railway vehicles instantly. The first stage is oriented towards the ambitious state-of-the-art.
- A second stage of limit values, for which binding definitions have to be found already at the present moment. The second stage is oriented towards a superior level (high noise-control performance level L_2).

Already at present it is possible to reach this stage as it is determined with on the basis of existing vehicles.

For the determination of limit values it must be observed that measurement results depend on various factors apart from a railway vehicle's noise emission. The measured results for railway vehicles scatter within a certain range.

The measurement uncertainty is influenced by

- sound level meters, calibrators,
- measurement methods,
- spread of noise emissions within a series of railway vehicles,
- quantities referred to the measured object.

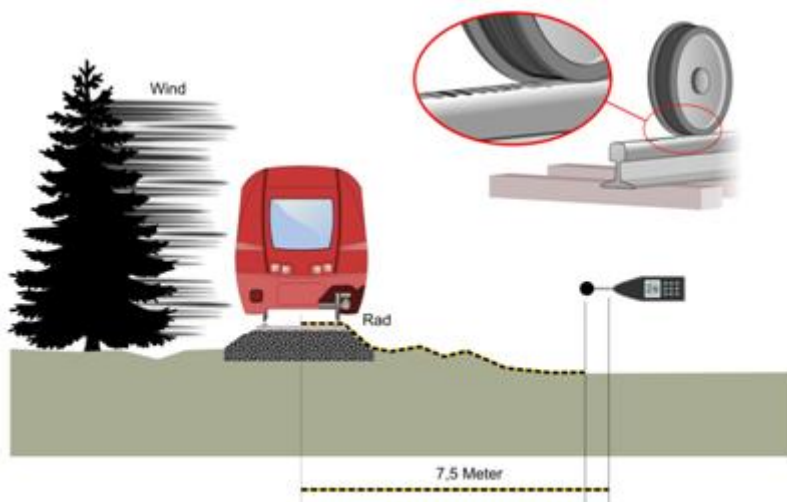


Figure 5. Parameters influencing the measurement accuracy [16].

Measurement errors have influence on individual measurement results, they are however averaged in the statistic parameters of a dataset, such as the median.

The track's impact is of high importance (formally belonging to the measurement method). It was determined as follows:

Influence and scattering of the noise emission as a consequence of different decay rates were determined in a measurement carried out by Müller-BBM. For this purpose, measurements were performed at a track complying with the TSI requirements for decay rates. After that, rail dampers were installed. The decay rate after establishing this measure was significantly over the limit curve according to the TSI noise.

Subsequently, the noise measurements were repeated. The difference between the two measurements was taken. A correction was made in order to revise the influence of noisier/quieter trains between the first and the second measurement series. The difference in noise emission was approx. the same value of 1.4 dB for all train types.

The stray interval was estimated to be 1.4 dB on the basis of the measured results. The standard deviation was determined under the assumption of a rectangular distribution and amounts to 0.4 dB.

The influence of the rail roughness of different test tracks was estimated by way of calculation. Basis for the investigations are data from acoustic type tests, in which the pass-by levels, the wheel roughness and the rail roughness were measured for a railway vehicle.

The sound pressure level of a railway vehicle in pass-by measurements on another test track was calculated under consideration of the measured pass-by level on a test track, the vehicle's measured wheel roughness and the roughnesses of both the test section and the comparison section. In total, the pass-by level was calculated for 12 sections from type tests, where Müller-BBM was in charge of the rail roughness measurements.

Calculations were done in third-octave bands, the conversion from wavelengths to frequencies was done via pass-by velocities. For each roughness variation the influence was determined for the pass-by noise in all third-octave bands. From the spectral behaviour the overall level was determined. Thus, for each dataset result in total 13 pass-by levels, one of the original section and 12 of the comparison section. The standard deviation was determined outgoing from the calculated sound pressure levels.

It was found in the calculation that the scattering of pass-by levels is strongly depending on the wheel roughness. For good wheels with third-octave spectra for roughness below the TSI limit curve standard deviations of approx. 1.0 dB occur. For bad wheels that clearly go beyond the TSI limit curve a minor influence of the rail roughness on the combined roughness is found. Here, standard deviations of 0.3 dB result. The average standard deviation of all datasets under investigation was 0.7 dB.

The (expanded) measurement uncertainty is determined by multiplying the combined standard uncertainty with a coverage factor k .

A confidence level of 95 % is assumed. In a one-sided test this is achieved by multiplying the standard deviation with a coverage factor k of 1.7. This means that only 5 % of the values lie by more than 1.7* standard deviation above the mean value. 95 % of the measured values are in the range below it.

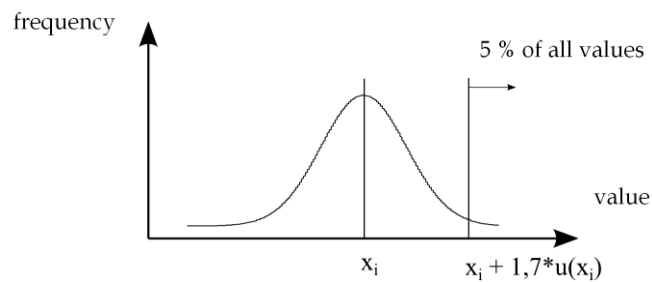


Figure 6. Standard normal distribution and 95 % confidence interval in a one-sided test.

For type test measurements the measuring devices as well as the track's influence are the most important influence to the measurement uncertainty. In total, a standard deviation of 1.3 dB was determined for the pass-by noise and of 1.0 dB for stationary noise. With the coverage factor of 1.7 that implies an expanded uncertainty of 1.7 for standing noise and an expanded measurement uncertainty of 2.2 for pass-by noise. Rounded, an expanded uncertainty of 2 dB comes out for both operating conditions. This measurement uncertainty of 2 dB is also set in for the starting up condition and taken into account in the determination of limit values.

Following the tradition of the TSI the limit value is composed as the sum of:
State-of-the-art value + measurement uncertainty.

Furthermore, two limit values are defined:

- Short-term applicable limit value:
Ambitious state-of the art + measurement uncertainty. The limit value, however, must not exceed the level of high noise-emission vehicles (upper limit L_1).
- Medium-term applicable limit value: High acoustic level L_2 + measurement uncertainty.

5 Proposals for limit values

Exemplarily, the determination of proposals for limit values for the stationary noise of diesel locomotives shall be presented first. After that the proposed limit values for all train categories and operating conditions shall be shown.

5.1 Stationary noise of diesel locomotives

For diesel locomotives there are no significantly changed measuring and operating conditions due to the updated TSI Noise. Versus the TSI Noise 2006 [2] the TSI Noise 2011 [4] only requires that the cooling systems of the driver's cab air-conditioning systems are run under minimal load. Their influence is of minor importance compared to other aggregates such as diesel engines or engine fans.

Result of the data collection, evaluation and noise reduction potential

The results for the stationary noise of diesel locomotives are displayed in the following figure:

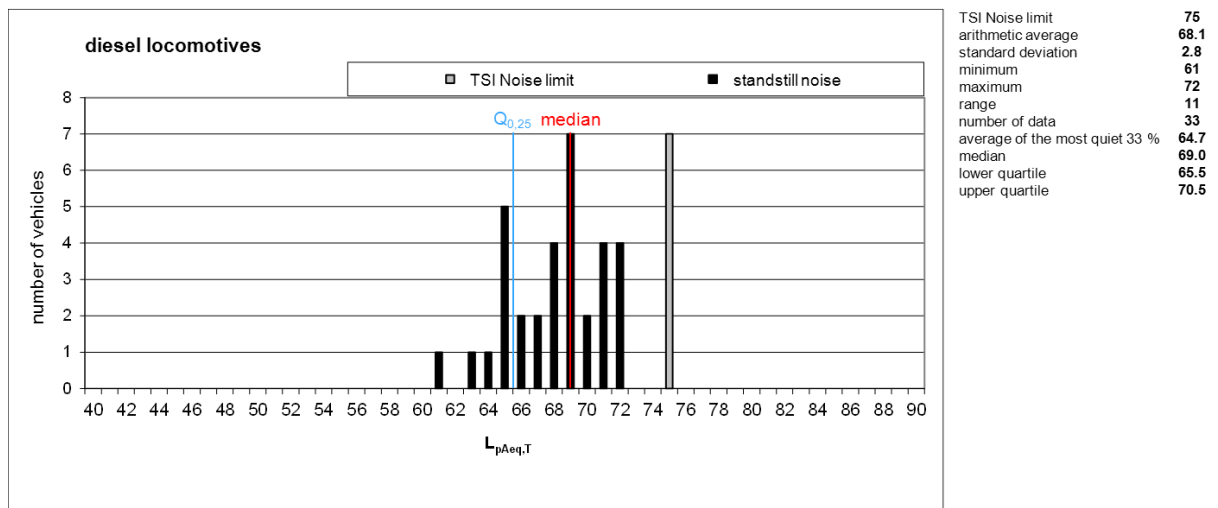


Figure 7. Results of the data collection for the standing noise of diesel locomotives, histogram and statistic parameters.

All vehicles are clearly below the limit value.

The noisiest of the recorded vehicles is by 3 dB under the limit value of $L_{pAeq,T} = 75$ dB, the quietest one even by 14 dB. The median is 6 dB below the limit value.

The data's standard deviation is 2.8 dB and so clearly above the standard deviation of standing noise measurements with 1.0 dB. This means that the essential impact is due to the different technologies applied.

A crucial impact of any building type to noise emission could not be observed.

The determined values for the state-of-the-art as well as the quietest vehicle in the category stationary noise of diesel locomotives are listed in the following table.

Table 3. Parameters identified from the data basis for the stationary noise of diesel locomotives.

Parameter	$L_{pAeq,T}$	Noise reduction potential
High noise emission machines according to EN ISO 11689 with L_1 for $x = 82,5 \%$	71 dB	4 dB
Moderate state-of-the-art (median)	69 dB	6 dB
Ambitious state-of-the-art (lower quantile)	66 dB	9 dB
Low noise emission machines according to EN ISO 11689 with L_2 for $x = 10 \%$	65 dB	10 dB

Development of limit value proposals

Stationary noise can easily be influenced with relatively simple methods, e.g.

- RPM-regulated fans,
- encapsulations or
- silencers.

The relevant techniques are available from the market, tested and are employed as it can be seen from the potential noise reduction measures and the realized quiet vehicles.

For the stationary noise of diesel locomotives we suggest the following limit values:

Table 4. Limit values for the stationary noise of diesel locomotives.

Limit values	$L_{pAeq,T}$	Noise reduction
Short-term applicable limit value (ambitious state-of-the-art + 2 dB measuring accuracy)	68 dB	7 dB
Mid-term applicable limit value (low noise emission machines according to EN ISO 11689 with L_2 for $x = 10 \%$ + 2 dB measuring accuracy)	67 dB	8 dB

In case the short-term applicable limit value is realized minor additional acoustic measures in the range of approx. 1 – 4 dB must be taken. Therefore, it can be assumed that the realisation of the short-term limit value will cause no significant additional costs for the rail sector. The same applies for the mid-term limit value, which is by 1 dB below the short-term limit value.

The indicated limit values can consequently be deemed to be feasible.

5.2 Limit value proposals

Altogether, the following proposals for limit values were developed:

Short-term limit values:

Table 5. Short-term limit values for the noise emission of railway vehicles in measurements according to the TSI Noise.

Train category	Stationary	Starting	Pass-by
	$L_{pAeq,T}$ in dB	L_{pAFmax} in dB	$L_{pAeq,Tp}$ in dB
Diesel locomotive	68	Diesel-electric: 80 Diesel-hydraulic: 84	85
Electric locomotive	63	P ≥ 4500 kW: 83 P < 4500 kW: 81	85
Diesel multiple unit	65	79	80
Electric multiple unit	57	73	77
Passenger coaches	57	--	77
Freight wagons	--	--	80 ²

Mid-term limit values:

Table 6. Mid-term limit values for the noise emission of railway vehicles in measurements according to the TSI Noise.

Train category	Stationary	Starting	Pass-by
	$L_{pAeq,T}$ in dB	L_{pAFmax} in dB	$L_{pAeq,Tp}$ in dB
Diesel locomotive	67	Diesel-electric: 80 Diesel-hydraulic: 84	83
Electric locomotive	59	P ≥ 4500 kW: 82 P < 4500 kW: 81	83
Diesel multiple unit	63	79	77
Electric multiple unit	53	73	77
Passenger coaches	53	--	76
Freight wagons	--	--	78 ²

Selected best-practice vehicles show that already nowadays railway vehicles are available from the market that are significantly quieter than the proposed limit values. Consequently, all proposed limit values can be realized.

² standardized to the reference APL according the CER proposal

$$L_{pAeq,Tp}(APL_{ref}) = L_{pAeq,Tp}(APL_{Wag}) - 10 \cdot \log\left(\frac{APL_{Wag}}{APL_{ref}}\right) \quad APL_{ref} = 0,225 \text{ 1/m} \quad [17]$$

With approx. 6,500 € – e.g. for a freight wagon for the realization of an APL-standardized pass-by level of $L_{pAeq,TP} = 75$ dB – the costs for noise mitigation measures are within reasonable limits (in which the costs here are mainly due to the use of composite brake blocks). The costs for wheel noise absorbers amount to approx. 1,500 € for a wheel set.

6 Best Practice Vehicles

As best practice vehicles were presented:

- The electric locomotive: LOK 2000
- The EMU Flirt Algier
- The low-floor double-decker rail coach NDW for commuter trains in Zurich
- The freight wagon of the working group ARGE Low Noise Train

7 Literature

- [1] TSI High Speed Rail Systems, 2002-05-30. Technical Specification for the interoperability relating to the rolling stock subsystem of the trans-European high-speed rail system (2002/735/EG).
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