RIGA TECHNICAL UNIVERSITY
Institute of railway transport

Andrei BARANOVSKII
Doctoral student of the study program „Computer management, Information and Electronic Systems of Transport"

EXPERIMENTAL INVESTIGATION AND MODELING OF RAILWAY TRANSPORT NOISE SPECTRA

Promotion thesis summary

Scientific supervisor
Dr. habil. phys., professor
V. POPOV

Riga 2013

UDK 656.2.053.7(043.2)
Ba 534 e

Baranovskii A. Experimental investigation and modeling of railway transport noise spectra. Promotion thesis summary. – R.: RTU, 2012. – 47 pp.

Printed according to the decision of the RTU promotion council „RTU P-20" at 20th of November 2012, protocol Nr. 4/2012.

This work has been supported by the European Social Fund within the project «Support for the implementation of doctoral studies at Riga Technical University».

ISBN 978-9934-10-403-9

PROMOTION THESIS IS PRESENTED FOR THE DEGREE OF DOCTOR OF ENGINEERING SCIENCES AT RIGA TECHNICAL UNIVERSITY

Promotion thesis for the degree of doctor of engineering sciences will be presented in the auditorium 218 at Riga Technical University, Institute of aeronautics, 1A, k-1 Lomonosova street, on the 21st of march 2013, at 14:30.

OFFICIAL REVIEWERS

Professor, Dr. habil. sc. ing. Aleksandrs URBAHS
Riga Technical University, Latvia

Professor, Dr. habil. sc. ing. Valerijs ZAGURSKIS
Riga Technical University, Latvia

Professor, Dr. sc. ing. Žilvinas BAZARAS
Kaunas University of Technology, Lithuania

CONFIRMATION

I confirm that this promotion thesis, presented for the degree of doctor of engineering sciences at Riga Technical University is my own original work. The promotion thesis is not presented for the degree at any other university.

Andrei BARANOVSKII …………………………….(Signature)

Date: ………………………

Thesis is written in English, contains introduction, 7 chapters, conclusions, list of references, 24 attachments, 129 figures, 204 pages in total. The list of references consists of 95 sources.

TABLE OF CONTENTS

GENERAL THESIS DESCRIPTION

Topicality of the thesis

The increase of speeds and transportation volumes of different types of transport, including railway transport, at the end of the 20-th and beginning of the 21-st century has led to rapid increase of acoustic smog, especially in large cities and megapolises.

As a result, in many countries the intensive scientific studies began in the field of acoustical noise spectra research, its modeling and recommendation development on safe and limiting levels.

During last years, in main part of Western European countries, the railway transport technologies were improved and there was permanent modernization with respect to noise level reduction in wide frequency range.

Unfortunately, till present time, there is a lag in this problem solution in many Eastern European countries. Therefore, after Latvia joined the EU, the necessity of scientific research studies appeared for Latvian railway in the field of noise spectra measurements and modeling, noise mapping and development of noise spectral level reduction methods, satisfying EU recommendations.

Aim of the thesis

The **aim** of the thesis is experimental investigation of Latvian railway transport traffic noise spectra, analysis of modern railway noise modeling methods and evaluation of EU recommended RMR (Reken - en Meetvoorschrift Railverkeerslawaai) modeling method's applicability on the Latvian railway.

To achieve the aim of the thesis, the following **tasks** are solved:

1. Analysis of railway noise sources and modern railway noise modeling methods.
2. Experimental measurements of pass by noise spectra of different rolling stock types with respect to current technology condition on Latvian railway.
3. Modeling of pass by noise spectra of different rolling stock types on Latvian railway with respect to current technology condition on Latvian railway and comparable analysis of measurement and modeling results.
4. Definition of new Latvian train types for modeling, using EU recommended method and development of recommendations for preparation of noise maps on Latvian railway in accordance with EU requirements.
5. Analysis of noise source reduction and noise abatement possibilities on Latvian railway.

Research methodology

Experimental investigations of noise spectra were performed using calibrated measurement equipment, meeting the requirement for class 1 measurement equipment specified in IEC 61672 and IEC 61260 and in accordance with LVS EN ISO 3095:2005. The measurement results were analyzed and statistically processed using commercial SVAN PC software from Svantek and Excel spreadsheets.

The noise spectra modeling was performed using MathCAD software, CadnaA noise mapping software and developed Train Noise Software (TNS).

Noise maps were developed using CadnaA software.

Scientific novelty

Thesis scientific novelty is in the original results of railway transport noise investigation on Latvian railway, which is significant contribution to the development of rail transport technology.

In thesis, the analysis of several railway noise modeling methods was performed and the EU recommended modeling method was improved, taking into account features of Latvian railway transport.

Practical significance

The results of experimental investigation of noise from different train types on Latvian railway can be used for the evaluation of train compliance with the requirements of technical specifications for interoperability.

The improved modeling method and practical recommendations will be used to improve the level of noise mapping accuracy on Latvian railway and during preparation of action plans for noise reduction.

Experimentally investigated acoustical effect of rail grinding will improve the quality of future rail reprofiling works.

Work results have been implemented within the framework of joint project of Riga Technical University (Institute of railway transport) and Latvian railway:

- "Dzelzceļa ritošā sastāva trokšņa mērījumu rezultātu apstrādes un kartēšanas metodikas izstrāde un dzelzceļa darbinieku apmācība", Nr. DFG-52/9669, 2011 – 2012;

within the framework of joint projects of Riga Technical University (Institute of railway transport), Latvian railway and Ministry of education and science of Republic of Latvia:

- „Latvijas dzelzceļa ritošā sastāva trokšņa starojuma un izplatīšanās matemātiskā modelēšana un eksperimentālie pētījumi", Nr. FLPP-2009/44, 2009;
- "Dzelzceļa objektu akustiskās emisijas modelēšana pilsētas intelektuālās transporta sistēmās", Nr. R7327, 2008.

Work results were used for development of the study modules on railway noise within the TEMPUS MISCTIF project, 2009 -2011.

Work results are used within the framework of project of Riga Technical University (Institute of railway transport) and Latvian railway:

- „Priekšlikumu VAS Latvijas dzelzceļš rīcības plānam trokšņu samazināšanai Rīgas pilsētā izstrāde", 2012;

and within the framework of project LIFE11 ENV/LV/376 ISRNM "Innovative Solutions for Railway Noise Management" under EC LIFE+ program, 2012 - 2015.

Defendable thesis

1) Investigation results, which showed relatively high noise levels of Latvian rolling stock in wide frequency range and allowed to define the character of change of spectra depending on the traffic speed, rolling stock type and railway track conditions.
2) Results of noise spectra modeling for Latvian railway, which allowed to define the limitedness of modeling method, recommended by EU for European railways.
3) Improved European modeling method with respect to Latvian railway conditions, based on software implemented algorithm of railway rolling stock pas by noise spectra calculation.

Approbation

Thesis results were presented and discussed at the following international scientific **conferences**:

1) The 19th International Congress on Sound and Vibration (ICSV'19), Vilnius, July 08-12, 2012. Topic of presentation – *Experimental investigation of railway noise and railway noise mapping in Latvia.*
2) The 7th International Scientific Conference Intelligent Technologies in Logistics and Mechatronics Systems (ITELMS'2012), Panevezys, May 03-04, 2012. Topic of presentation – *Railway noise in Latvia.*

3) The 52nd International Scientific Conference of Riga Technical University, Riga, Oct. 15, 2011. Topic of presentation – *Railway noise abatement at Plavinas gymnasium.*
4) The International Scientific Conference Signal and Image Processing and Applications (SIPA 2011), Crete, June 22-24, 2011. Topic of presentation – *Application of RMR method for noise prediction on Latvian railway.*
5) The 7th International Scientific Conference Transbaltica 2011, Vilnius, May 05-06, 2011. Topic of presentation – *Adaptation of RMR noise propagation prediction method for Latvian railway conditions.*
6) The 51st International Scientific Conference of Riga Technical University, Riga, Oct. 11-15, 2010. Topic of presentation – *Update of CadnaA noise map based on measurement results.*
7) The 51st International Scientific Conference of Riga Technical University, Riga, Oct. 11-15, 2010. Topic of presentation – *General overview of predictive acoustics for railway transport.*
8) The 5th International Scientific Conference Intelligent Technologies in Logistics and Mechatronics Systems (ITELMS'2010), Panevezys, June 03-04, 2010. Topic of presentation – *Comparison of five national noise emission calculation methods for rail traffic.*
9) The 50th International Scientific Conference of Riga Technical University, Riga, Oct. 14-16, 2009. Topic of presentation – *Railway rolling stock noise experimental measurements.*
10) The 50th International Scientific Conference of Riga Technical University, Riga, Oct. 14-16, 2009. Topic of presentation – *Adequacy evaluation of railway rolling stock noise models.*
11) Rīgas Tehniskās universitātes 49. starptautiskā zinātniskā konference, Rīga, Okt. 13-15, 2008. Prezentācijas tēma – *Dzelzceļa trokšņa CRN matemātiskais modelis.*
12) Rīgas Tehniskās universitātes 49. starptautiskā zinātniskā konference, Rīga, Okt. 13-15, 2008. Prezentācijas tēma – *Dzelzceļa objektu radītā trokšņa eksperimentālie mērījumi.*

Based on thesis results **reports** on three projects were prepared, presented and discussed at Latvian railway:

1) "Dzelzceļa ritošā sastāva trokšņa mērījumu rezultātu apstrādes un kartēšanas metodikas izstrāde un dzelzceļa darbinieku apmācība", Nr. DFG-52/9669, 2012.
2) „Latvijas dzelzceļa ritošā sastāva trokšņa starojuma un izplatīšanās matemātiskā modelēšana un eksperimentālie pētījumi", Nr. FLPP-2009/44, 2009.
3) "Dzelzceļa objektu akustiskās emisijas modelēšana pilsētas intelektuālās transporta sistēmās", Nr. R7327, 2008.

Thesis results were presented and discussed during **lectures** within the framework of the TEMPUS MISCTIF project:

1) Dnepropetrovsk National University of railway transport named after academician V. Lazaryan, Feb. 24-25, 2011, 12 hours.
2) Kyrgyz State University of Construction, Transport and Architecture named after N. Isanov, May 16-17, 2011, 12 hours.
3) Kazakh academy of transport and communications named after M. Tynyshpayev, May 19-20, 2011, 12 hours.

The following **papers** containing thesis results and related to thesis topic were published:

1) Baranovskii A. Experimental investigation of railway noise and railway noise mapping in Latvia // Proceedings of the 19th International Congress on Sound and Vibration (ICSV'19), Lithuania, Vilnius, July 08-12, 2012. – 8 pp. (CD-ROM)
2) Baranovskii A. Railway noise in Latvia // Proceedings of the 7th International Scientific Conference Intelligent Technologies in Logistics and Mechatronics Systems (ITELMS'2012), Lithuania, Panevezys, May 03-04, 2012. – 33 – 37 pp.
3) Baranovskii A. Railway noise abatement at Plavinas gymnasium // Scientific proceedings of RTU. Transport and engineering. Railway transport. – 2012. – Series 6, Vol. 34. – 3 pp. (accepted for publishing)
4) Baranovskii A. Computer simulation and experimental investigations of noise levels and spectra for railway transport // Automatic control and computer sciences. – 2011. - Vol. 45, Nr. 5. – 293-300 pp. (springerlink, scopus)
5) Барановский А. Компьютерное моделирование и экспериментальные исследования уровней и спектров шумов от железнодорожного транспорта // Автоматика и вычислительная техника. - 2011. - Н. 5. – 69-78 с. (viniti)
6) Baranovskii A. Application of RMR method for noise prediction on Latvian railway // Proceedings of the International Scientific Conference Signal and Image Processing and Applications (SIPA 2011), Greece, Hersonissos, June 22-24, 2011. - 33–38 pp. (actapress)
7) Baranovskii A. Adaptation of RMR noise propagation prediction method for Latvian railway conditions // Proceedings of the 7th International Scientific Conference TRANSBALTICA 2011, Lithuania, Vilnius, May 05-06, 2011. – 11-15 pp. (VGTU online library)
8) Balckars P., Baranovskii A., Popov V. General overview of predictive acoustics for railway transport // Scientific proceedings of RTU. Transport and engineering. Railway transport. – 2011. – Series 6, Vol. 33. – 3 pp. (accepted for publishing)
9) Baranovskii A. Comparison of five national noise emission calculation methods for rail traffic // Proceedings of the 5th International Scientific Conference Intelligent Technologies in Logistics and Mechatronics Systems (ITELMS'2010), Lithuania, Panevezys, May 03-04, 2010. – 7-12 pp. (scopus)
10) Попов В., Балцкарс П., Барановский А., Ильина Л. Экспериментальные исследования уровней шума железнодорожного подвижного состава // Scientific proceedings of RTU. Transport and engineering. Railway transport. – 2008. – Series 6, Vol. 30. – 29-37 pp.
11) Попов В., Балцкарс П., Барановский А. Математическая модель CRN шума железнодорожного подвижного состава // Scientific proceedings of RTU. Transport and engineering. Railway transport. – 2008. – Series 6, Vol. 30. – 21-29 pp.

Structure of thesis

Thesis consists of introduction, seven chapters, conclusions, list of references and attachments.

- In Chapter 1 the main railway noise sources are analyzed, particularly rolling noise. Some of the possible ways of vibration modeling of rolling noise main component sources: rails, wheels and sleepers are discussed.
- In Chapter 2 is analyzed sound radiation by simple and main rolling noise component sources.

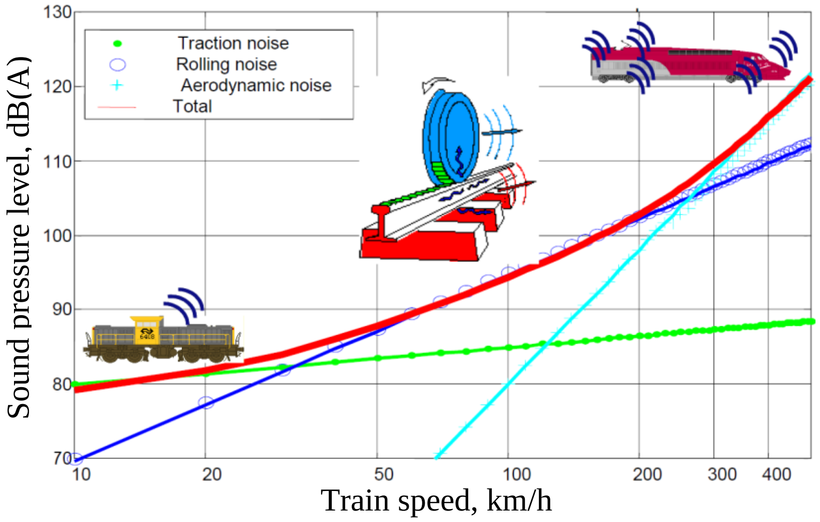
- In Chapter 3 are analyzed main features of sound propagation in the air; deterministic, statistical, semiempirical and empirical models of railway noise emission and propagation are analyzed and the detailed description of the EU recommended RMR (Reken - en Meetvoorschrift Railverkeerslawaai) octave band method for railway noise modeling is provided.
- In Chapter 4 are analyzed modern railway noise experimental investigation methods; results of railway noise experimental investigations on Latvian railway are analyzed; comparable analysis of railway noise modeling and experimental investigation results on Latvian railway is performed; the developed and software implemented algorithm (TNS – Train Noise Software) of railway rolling stock pass by noise spectra calculation is described and RMR method is improved with respect to Latvian railway conditions.
- In Chapter 5 the railway noise mapping, particularly for Riga agglomeration is analyzed and the approach of accuracy improvement of noise mapping results in Latvian railway condition using TNS is proposed.
- In Chapter 6 are analyzed modern railway noise source reduction and noise abatement methods.
- In Chapter 7 the prospects for enhancement of legislative and standard base in the field of acoustic ecology with respect to railway noise are discussed.

1. ANALYSIS OF RAILWAY NOISE SOURCES

Railway transport is very specific in the terms of noise source estimation and separation. For the noise control purposes, the estimation of train and track impact to the overall noise level being radiated is of a very high importance. But due to the problem complexity, in Europe, only in 2002 were introduced first legal limits on the noise, radiated by individual rail vehicles, which became the part of the "Technical specifications for interoperability" (TSI) [27].

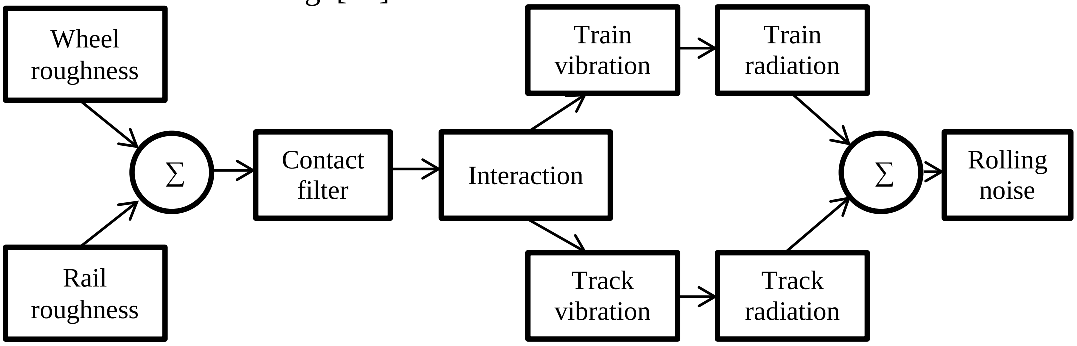
There are many possible sources of railway noise and the dominant source may vary in different situations. However, in normal operating conditions, the major source for railway noise is usually rolling noise caused by interaction of rails and wheel pairs of train running on straight track. Other important noise sources are traction and aerodynamic noise. Traction noise is less dependent on train speed and usually found to be dominant at low speeds. Most dependent on the train speed is the aerodynamic noise which becomes dominant at high speeds. Occurrence of curve squeal noise, braking noise, impact noise from rail joints or wheel flats and train horn signals may easily increase the total noise level by 20-30 dB.

The 1.1. fig. illustrates the speed dependency of main railway noise sources and their impact to the total noise level [29].



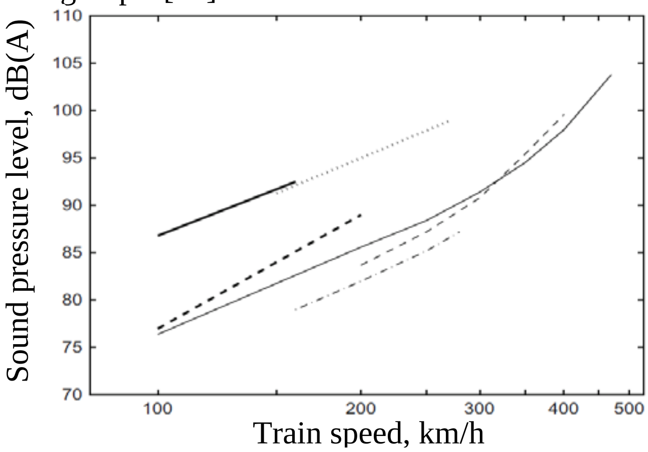
1.1. fig. Railway noise sources and typical dependency on train speed

It can be seen in the 1.1. fig., that rolling noise is the most important noise source for train speeds below 250 km/h. Rolling noise depends on the roughness and corrugation of wheel pairs and rails. During train passage, roughness in the wheel and rail contact area causes vertical vibrations, both, in train and track. The simplified mechanism of rolling noise generation is illustrated in 1.2. fig. [16]



1.2. fig. The mechanism of rolling noise generation

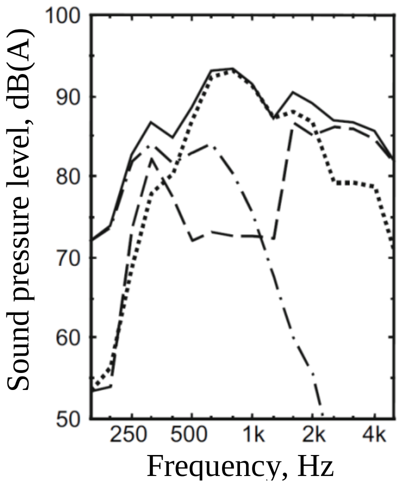
Rolling noise has a broad-band nature with many different resonant frequencies for wheels, rails, sleepers, bogies, etc. Rolling noise is also speed dependent, because wheel and rail roughness will correspond to different noise frequencies with respect to the train speed. The main wavelengths of roughness that are relevant to rolling noise are between 5 mm and 500 mm. Examples of train pass-by noise levels measured at 25 m distance from track central line for different types of trains are shown in 1.3. fig. It can be seen from the results that in terms of rolling noise levels trains can be divided in two groups: trains with cast-iron block brakes and trains with other type of brake system. There is 8 dB(A) to 10 dB(A) difference in noise levels between these two groups. [16]



1.3. fig. Measurement results of train pass-by noise from different types of trains

Tread braked vehicles: ━, BR Mk II coaches; ·····, TGV-PSE; Disc-braked vehicles: ━ ━ ━, BR Mk III coaches; —, TGV-A, Duplex and Thalys; – – –, ICE/V; · – · – ·, Talgo (drum brakes)

From the acoustical point of view the train/track system is a very complex system consisting of large number of independent sources, all having their own physical and acoustical characteristics. It is practically impossible to analytically describe the whole system taking into account the entire component sources with respect to all radiation affecting parameters. However, since the total sound pressure level at some point of reception will be represented by the energetic summation of all contributing sources, for practical applications it is usually enough to describe the dominant sources.



1.4. fig. Example of TWINS simulation results

— total, 100 dB(A); - - - wheel, 94.4 dB(A), ····· rail, 98.3 dB(A); -·-·- sleeper, 87.2 dB(A)

The most important component sources of rolling noise are wheels, rails and sleepers. Sleepers make the most impact in the low frequency range, rails in the mid frequency range and wheels in the high frequency range. In 1.4. fig. the example of TWINS (train wheel interaction software) simulation results for total, wheel, rail and sleeper noise is shown.

Simulation was performed for a freight vehicle at the speed of 100 km/h on track with a relatively soft rail pad (200 MN/m). [16]

Since rolling noise is the product of component source vibrations, the first step in rolling noise modeling is related to source vibration estimation. Various simplified and more elaborate models and methods are available for rolling noise component source vibration modeling. Some of these methods are discussed in chapter 1 of the thesis.

2. ANALYSIS OF SOUND RADIATION FROM STRUCTURAL VIBRATIONS

The sound power radiated by vibrating structure can be described with the help of radiation ratio. The radiation ratio depends on source dimensions and tends to unity when source size is large compared to sound wavelength. To describe the proportion of sound power radiation in different directions, the directivity factor is used.

The dominant rolling noise component sources: wheels, rails and sleepers can be adequately represented by simple sources with known radiation ratios and directivity factors, such as monopoles, dipoles, multipoles and line sources. In this thesis chapter are considered both, simple sources and rolling noise component source representation by simple sources.

3. ANALYSIS OF RAILWAY NOISE RADIATION AND PROPAGATION PREDICTION METHODS

When the source radiated sound power is known, the estimation of the sound level at some point of receptions becomes possible. However, to estimate the sound pressure level at some point of reception it is necessary to take into account many aspects of sound wave propagation in the media. Railway noise propagation is influenced by ground effects, atmospheric absorption, wind and temperature gradients, obstacles (reflective or absorptive) and foliage in the propagation path, etc. Moreover, the situation is complicated by the movement of the source (train).

Various analytical models and methods, with certain limitations, can be used to describe sound propagation under different conditions and with relatively high level of accuracy, however high level of accuracy is often demanding for computational resources. In 3.1. table are described some of the widely used models and methods for sound propagation prediction in the air: EULER – Linearized Eulerian model, BEM – Boundary Element Method, METBEM – Meteo-BEM, PE – parabolic equation method, GTPE – generalized terrain PE, FFP – fast field program, SRAY – straight-ray model for a non-refracting atmosphere, CRAYL – curved-ray model for a refracting atmosphere using a linearized sound speed profiles, STAT – various statistical scattering models. [12]

The results of undertaken within the HARMONOISE project [14] benchmark tests of models and methods listed in 3.1. table showed that EULER, BEM, and the PE methods (PE and GTPE) are accurate in most cases. Of these basic models, only the EULER and PE methods can take into account the realistic meteorological conditions. The main problem of using EULER model is the very large computational effort required. The two-dimensional PE method is a good alternative in terms of accuracy and computational effort ratio.

In situations in which the PE method cannot be applied and in which refraction may be neglected, SRAY or BEM can be used. In principle, BEM could be used in all of these situations, because the applicability of BEM is larger than the applicability of SRAY. However, because of its smaller computational effort, usage of SRAY instead of BEM is preferable in situations where SRAY is applicable and accurate.

Statistical scattering models can be used for sound propagation modeling in forests and cities. [15]

3.1. table

Models and methods of the sound propagation

Model	Limitations	Computational effort
EULER	no limitations, except for approximate representation of ground impedance	very large
BEM	limited to a non-refracting atmosphere	large
METBEM	limited to linear sound speed profiles	large
PE	limited to axisymmetric cases, maximum propagation angles between 35 and 70 degrees, forward propagation, rectangular obstacles and a flat ground	large
GTPE	same as for PE, but applicable to arbitrary terrain profiles with a maximum local slope of 30 degrees	large
FFT	limited to axisymmetric cases, a layered atmosphere, no obstacles and a flat homogeneous ground	large
SRAY	limited to a non-refracting atmosphere, dimensions of obstacles and distances to diffraction edges that are large compared to wavelength, and obstacles that consist of flat surfaces	small
CRAY	same as for SRAY, but not limited to a non-refracting atmosphere	small
STAT	limited to a non-refracting atmosphere and randomly distributed scattering objects that are small compared to wavelength	small

For practical applications, such as noise map development, it is physically not possible to take into account all of the parameters, required for calculations using the analytical models only for vibration, sound radiation and propagation. Therefore, approximated and statistically averaged empirical models of sound radiation and propagation are used.

In many EU member states national methods for railway noise modeling were developed and used for more than two decades. In 3.2. [3] table are shown results of comparable analysis of several national methods: RMR (the Netherlands, interim method for EU) [9, 24, 25], Schall 03 (Germany) [9, 25], ON S5011 (Austria) [9, 25], CRN (United Kingdom) [11, 17], NMPB (France) [9], NMT (Nordic countries) [9, 25], Nord2000 (new generation method for Nordic countries) [9, 25], HARMONOISE engineering method [13].

It is important to mention that national methods in many countries are regularly reviewed and updated, therefore, the results of performed analysis might have lost actuality due to information limited availability. To the best of author's knowledge, French and German methods were improved recently.

The most advanced of compared methods is the HARMONOISE method. The aim of HARMONOISE project was the development of modeling method, common for all EU member states, however many countries are satisfied with their national methods and are not motivated to invest in reconsidering the HARMONOISE as the new national method, therefore developed method was not yet officially approved. Another reason for so long process of HARMONOISE result approval is the lack of the technical tools to be used with the method, such as noise mapping software. Main successors of HARMONOISE project are Northern countries, which actively participated in the project and in parallel had developed the new national method Nord2000. The Netherlands national method RMR can be considered as the second most detailed method and is recommended by EC in directive on environmental noise 2002/49/EC as interim railway noise modeling method for EU member states. From the level of detail point of view, RMR method is followed by NMT with less detailed track influence description, ONS5011 and NMPB with lower number of available source heights and CRN with SCHALL03, not offering calculation of radiation spectra.

Taking into account results of comparable analysis and EC recommendations, the RMR method was chosen for detailed evaluation in the thesis.

3.2. table

Differences between national railway noise modeling methods

Characteristics	Method			
	SCHALL03	ONS5011	CRN	NMPB
Basic noise parameter	LAeq at reference distance 25 m and 4 m height, based on measurements, the radiation is a function of train category, length, percentage of disc brakes and speed	Octave band sound power level, calculated from measurements at different distances and heights, the radiation is a function of train category and speed	LAeq at reference distance 25 m and 1.2 to 4 m height, calculated based on SEL levels, the radiation is a function of train category, speed and number of vehicles in the train	Measured at reference distance 25 m and 3.5 m height noise levels in octave bands
Spectrum	-	63 Hz to 8 kHz octave bands	-	125 Hz to 4 kHz octave bands
Location of source	One source at railhead level	One source 0.3 m above railhead	One source at railhead level	80 cm and 5 cm above railhead
Speed dependency	For A-weighted levels	For each octave band	For SEL and A-weighted levels	For each octave band
Track influence	4 different classes, no frequency dependency	3 different classes, no frequency dependency	6 different classes, no frequency dependency	-
Influence of joints, switches, crossings and bridges	-	-	Table of frequency independent correction coefficients	-
Specific parameter	-	-	-	-
Characteristics	Method			
	RMR	NMT	Nord2000	HARMONOISE
Basic noise parameter	Octave band sound power level for each source per meter of rail length as a function of train category, speed and traffic intensity	Octave band sound power level per meter of train length, calculated from measurements at different distances and heights	Third octave band sound power level per meter of train length, calculated from measurements at different distances and heights	Third octave band sound power levels for moving point sources at 5 heights
Spectrum	From 63 Hz to 8 kHz	From 63 Hz to 8 kHz	From 25 Hz to 10 kHz	From 25 Hz to 10 kHz
Location of source	Up to 4 sources with different heights: at railhead, 0.5 m, 2 m, 4 m and 5 m above railhead	One source for each octave band with its specific source height	0.01 m, 0.35 m and 0.7 m heights above railhead for rolling noise and actual heights for aerodynamic and traction noise	5 sources at different heights: at railhead, 0.5 m, 2 m, 3 m and 4 m above railhead
Speed dependency	For each octave band and source	For each octave band and source	For each third octave band and source	For each third octave band and source
Track influence	8 different classes, corrections are frequency dependent	Corrections from -6 dB to +6 dB, but no specific classification, no frequency dependency	4 track categories divided in 3 subcategories based on rail roughness	Large database of speed and frequency dependent corrections
Influence of joints, switches, crossings and bridges	Table of frequency dependent correction coefficients	Table of frequency independent correction coefficients	Correction table, correction not frequency dependent	Large database of speed and frequency dependent corrections
Specific parameter	Local rail and wheel roughness consideration, braking noise is accounted	Positive temperature gradients and downwind	Weather conditions and acceleration is considered	Wheel and rail roughness profiles are accounted in third octave bands, lots of separate sources are considered, complex weather conditions, diffraction schemes and scattering from trees is considered, correction for accelerating, decelerating and squeal noise is provided, Fresnel zone weighting applied

Brief description of the RMR octave band method

There are three train type categories currently in operation on Latvian railway, which correspond to those described (11 in total) in RMR: electric passenger trains - RMR category 1, diesel passenger trains - RMR category 6 and freight trains – RMR category 4, therefore the description of calculation method will be limited to these three categories.

For these three train categories 2 source heights are defined in RMR: L_{bs} – at the level of the railhead representing the track radiated noise and L_{as} – 0.5 m above the railhead representing the wheel rolling noise.

The basic formula for the calculation of radiated sound power level, dB(A), by non-braking (index nr) trains of category c in the octave band i for the period of one hour is [25]:

$$E_{nr,i,c} = a_{i,c} + b_{i,c} \log_{10}\left(\frac{v_{nr}}{v_0}\right) + 10\log_{10}\left(\frac{Q_{nr}}{Q_0}\right) + C_{bb,m,i}, \tag{3.1}$$

where $a_{i,c}$ and $b_{i,c}$ – radiation indexes defined for each train category c and each octave band i from 3.3. table; v_{nr} – average train speed, km/h; v_0 – normalizing value, 1 km/h; Q_{nr} – traffic intensity, i.e. number of trains per hour, h^{-1}; Q_0 – normalizing value, 1 h^{-1}; $C_{bb,m,i}$ – track correction for track type bb from 3.5. table and rail disconnection class m from 3.6. table.

3.3. table

Radiation indexes a and b for three train categories in eight octave bands

Train category c	Radiation index	Octave band center frequency, Hz and number i							
		63	125	250	500	1000	2000	4000	8000
		1	2	3	4	5	6	7	8
1	a	20	55	86	86	46	33	40	29
	b	19	8	0	3	26	32	25	24
4	a	30	74	91	72	49	36	52	52
	b	15	0	0	12	25	31	20	13
6	a, v<60	54	50	66	86	68	68	45	39
	b, v<60	0	10	10	0	10	10	20	20
	a, v≥60	36	15	66	68	51	51	27	21
	b, v≥60	10	30	10	10	20	20	30	30
6 engine	a, v<60	72	88	85	51	62	54	25	15
	b, v<60	-10	-10	0	20	10	20	30	30
	a, v≥60	72	35	50	68	9	71	1	-3
	b, v≥60	-10	20	20	10	40	10	40	40

The same calculation is performed for braking trains (index r) [25]:

$$E_{r,i,c} = a_{i,c} + b_{i,c} \log_{10}\left(\frac{v_r}{v_0}\right) + 10\log_{10}\left(\frac{Q_r}{Q_0}\right) + C_{bb,m,i} \tag{3.2}$$

And the braking noise is accounted as [25]:

$$E_{brake,i,c} = a_{i,c} + b_{i,c} \log_{10}\left(\frac{v_r}{v_0}\right) + 10\log_{10}\left(\frac{Q_r}{Q_0}\right) + C_{brake,i,c}, \tag{3.3}$$

where $C_{brake,i,c}$ – correction for braking noise for train category c in octave band i from 3.4. table.

3.4. table

Correction factor $C_{brake,i,c}$ as a function of octave band i and train category c

Octave band i	$C_{brake,i,c}$	
	c = 1, 4	c = 6
1	-20	-20
2	-20	-20
3	-20	-20
4	-2	-20
5	2	-20
6	3	-20
7	8	-20
8	9	-20

For diesel passenger trains additional correction for engine noise can be applied in the same form for both non-braking and braking trains [25]:

$$E_{engine,i,c} = a_{engine,i,c} + b_{engine,i,c} \log_{10}\left(\frac{v}{v_0}\right) + 10\log_{10}\left(\frac{Q}{Q_0}\right) \quad (3.4)$$

3.5. table

Correction coefficients $C_{bb,i}$ as a function of track type bb and octave band i

Octave band i	$C_{bb,i}$							
	bb=1	bb=2	bb=3	bb=4	bb=5	bb=6	bb=7	bb=8
1	0	1	1	6	6	-	6	5
2	0	1	3	8	8	-	1	4
3	0	1	3	7	8	-	0	3
4	0	5	7	10	9	-	0	6
5	0	2	4	8	2	-	0	2
6	0	1	2	5	1	-	0	1
7	0	1	3	4	1	-	0	0
8	0	1	4	0	1	-	0	0

In case of rail disconnection class m=1 (jointless rails), the correction coefficient $C_{bb,i,m}$ is taken from 3.5. table. For other disconnection classes, 3.6. table, the correction coefficient $C_{bb,i,m}$ is given by [25]:

$$C_{bb,i,m} = C_{3,i} + 10\log_{10}(1 + f_m A_i), \quad (3.5)$$

where $C_{3,i}$ – correction values from 3.5. table for bb=3; f_m – is taken from 3.6. table; A_i – is taken from 3.7. table.

3.6. table

Rail disconnection class m description

Description	m class	f_m
Track with rail joints	2	1/30
1 switch	2	1/30
2 switches per 100 m	3	6/100
More than 2 switches per 100 m	4	8/100

3.7. table

Correction factor A_i as a function of octave band i

Octave band i	A_i
1	3
2	40
3	20
4	3
5, 6, 7, 8	0

As it was discussed in chapter 1, the rolling noise is highly dependent on the roughness profiles of rails and wheels. In RMR method the average national wheel and rail roughness for Dutch railway networks is included in correction coefficients $C_{bb,i,m}$. In case of rails with joints, the roughness is less important, because the rolling noise radiation will be dominated by impact noise from joints, however in case of jointless rails (m = 1), the rolling noise levels can vary significantly due to differences between local and national average rail and wheel roughness profiles. Therefore for jointless rails $C_{bb,i}$ is modified by [25]:

$$C_{c,bb,i} = C_{c,bb,i} - \left(L_{i,rtr,ni}(\lambda_i) \oplus L_{i,rveh,ni,c}(\lambda_i)\right) + \left(L_{i,rtr,loc}(\lambda_i) \oplus L_{i,rveh,loc,c}(\lambda_i)\right), \quad (3.6)$$

where $C_{bb,i}$ – is taken from 3.5. table; $L_{i,rtr,ni}(\lambda_i)$ and $L_{i,rtr,loc}(\lambda_i)$ – correspondingly average national and local rail roughness, dBmkm; $L_{i,rveh,ni,c}(\lambda_i)$ and $L_{i,rveh,loc,c}(\lambda_i)$ - correspondingly average national and local wheel roughness for train category c, dBmkm; λ_i – roughness wavelength, m; $\oplus$ - energetic summation operation.

The roughness profile can be measured using different direct and indirect measurement techniques discussed in chapter 4.

For electric and diesel passenger trains the noise radiation at the source heights L_{bs} and L_{as} is given by [25]:

$$E_{bs,nr,i,c} = E_{bs,r,i,c} = E_{nr,i,c} - 1 \quad (3.7)$$

$$E_{as,nr,i,c} = E_{as,r,i,c} = E_{nr,i,c} - 7 \quad (3.8)$$

For freight trains the noise radiation at the source heights L_{bs} and L_{as} is given by [25]:

$$E_{bs,nr,i,c} = E_{bs,r,i,c} = E_{as,nr,i,c} = E_{as,r,i,c} = E_{nr,i,c} - 3 \quad (3.9)$$

The correction constants show that for Dutch railway network track is the dominant rolling noise source in case of electric and passenger trains. In case of freight trains wheels and track contributions to rolling noise assumed to be equal.

The radiated sound power level, dB(A), by non-braking and braking trains of n categories present at the source heights L_{bs} and L_{as} in octave band i for the period of one hour is calculated by [25]:

$$L_{E,i}^{bs} = 10\log_{10}\left(\sum_{c=1}^{n} 10^{E_{bs,nr,i,c}/10} + 10^{E_{bs,r,i,c}/10}\right) \quad (3.10)$$

$$L_{E,i}^{as} = 10\log_{10}\left(\sum_{c=1}^{n} 10^{E_{as,nr,i,c}/10} + 10^{E_{as,r,i,c}/10} + 10^{E_{brake,i,c}/10} + 10^{\frac{E_{engine,nr,i,c} \oplus E_{engine,r,i,c}}{10}}\right) \quad (3.11)$$

It can be seen from (3.11) that in the RMR the engine and braking noise source height is defined at 0.5 m above railhead.

The A-weighted sound pressure spectrum in the point of reception is found by calculation of sound pressure level in each octave band i due to source n using [25]:

$$\Delta L_{eq,i,n} = L_{E,n} + L_{GU} - L_{OD} - L_{SW} - L_R - 58.6, \quad (3.12)$$

where $\Delta L_{eq,i,n}$ - sound pressure level in the point of reception, dB(A); $L_{E,n,i}$ - radiated sound power level, dB(A), due to source n in octave band i (3.10, 3.11), dB(A); L_{GU} – attenuation due to distance, dB; L_{OD} – attenuation due to propagation, dB; L_{SW} – screening effect if present, dB; L_R – reflection effect if present, dB.

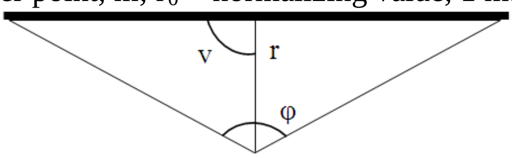
The constant value of 58.6 accounts for various corrections such as reference values and the conversion of sound power to sound pressure containing distance and surface quantities.

The equivalent A-weighted sound pressure level (dB(A)) in the point of reception is calculated energetically summating pressures due to all sources N in all octave bands i [25]:

$$L_{Aeq} = 10\log_{10}\sum_{n=1}^{N}\sum_{i=1}^{8} 10^{\Delta L_{eq,i,n}/10} \quad (3.13)$$

$$L_{GU} = 10\log_{10}\left(\frac{(\varphi/\varphi_0)\sin v}{r/r_0}\right), \quad (3.14)$$

where φ and v – angles shown in 3.1. fig.; φ_0 – normalizing value, 1°; r – distance from track center line to receiver point, m; r_0 – normalizing value, 1 m.



3.1. fig. Angles φ, v and measurement distance r

Attenuation due to propagation is given by [25]:

$$L_{OD} = D_L + D_B + C_M, \quad (3.15)$$

where D_L – attenuation due to air absorption, dB; D_B – attenuation due to ground effect, dB; C_M – meteorological correction factor, dB.

$$D_L = r\delta_{air}\,, \tag{3.16}$$

where δ_{air} – air absorption coefficient in accordance to ISO 9613-2 [81].

$$C_M = C_0\left(1-10\frac{h_h+h_w}{r_0}\right) \qquad \text{for} \qquad r_0 > 10(h_h+h_w)$$

$$C_M = 0 \qquad \text{for} \qquad r_0 \le 10(h_h+h_w), \tag{3.17}$$

where h_h – source height above the average terrain level in the source area, m; h_w – height of the point of reception above the average terrain level in the assessment area, m; r_0 – horizontally measured distance between source and the point of reception, m; C_0 – constant which depends on the local meteorological statistics for wind speed and direction and temperature gradients, typical value is in the range from 0 dB to 5 dB.

When determining the attenuation due to ground effect D_B, the horizontally measured distance between the source and the point of reception is divided into three areas: source area, middle area and assessment area. The source area has a length of 15 m and the assessment area a length of 70 m. The remaining section of the distance r_0 between the source and the assessment point forms the middle area. If the distance between the source and the point of reception is less than 85 m, the length of the middle area is zero.

If the distance r_0 is less than 70 m, the length of the assessment area is equal the distance r_0.

If the distance r_0 is less than 15 m, both the length of the source area and the assessment area is equal the distance r_0.

The ground absorption factor is calculated for all three areas.

To calculate the ground attenuation the following factors are taken into account: r_0, h_h, h_w, B_b – ground absorption factor in the source area, B_m - ground absorption factor in the middle area, B_w - ground absorption factor in the assessment area, S_w effectiveness of ground attenuation inside the assessment area, S_b effectiveness of ground attenuation inside the source area. If h_h is less than zero, the value zero is given to h_h and the same applies for h_w.

The ground attenuation is calculated using equations listed in the following table [25]:

3.8. table

Determination of ground absorption as a function of the octave band i

i	Ground attenuation, dB			
1		$-3\gamma_0(h_h+h_w,r_0)$		-6
2	$[(S_h\gamma_2(h_h,r_0)+1)B_b]$	$-3(1-B_m)\gamma_0(h_h+h_w,r_0)$	$[(S_w\gamma_2(h_h,r_0)+1)B_w]$	-2
3	$[(S_h\gamma_3(h_h,r_0)+1)B_b]$	$-3(1-B_m)\gamma_0(h_h+h_w,r_0)$	$[(S_w\gamma_3(h_h,r_0)+1)B_w]$	-2
4	$[(S_h\gamma_4(h_h,r_0)+1)B_b]$	$-3(1-B_m)\gamma_0(h_h+h_w,r_0)$	$[(S_w\gamma_4(h_h,r_0)+1)B_w]$	-2
5	$[(S_h\gamma_5(h_h,r_0)+1)B_b]$	$-3(1-B_m)\gamma_0(h_h+h_w,r_0)$	$[(S_w\gamma_5(h_h,r_0)+1)B_w]$	-2
6	B_b	$-3(1-B_m)\gamma_0(h_h+h_w,r_0)$	$+B_w$	-2
7	B_b	$-3(1-B_m)\gamma_0(h_h+h_w,r_0)$	$+B_w$	-2
8	B_b	$-3(1-B_m)\gamma_0(h_h+h_w,r_0)$	$+B_w$	-2

The functions $\gamma(x,y)$ in 3.8. table are determined using (3.18 – 3.22) [25].

$$\gamma_0(x,y) = 1-30\frac{x}{y} \qquad \text{for} \qquad y \ge 30x$$

$$\gamma_0(x,y) = 0 \qquad \text{for} \qquad y < 30x \tag{3.18}$$

$$\gamma_2(x,y)=3\left(1-e^{\frac{-y}{50}}\right)e^{-.012(x-5)^2}+5.7\left(1-e^{-2.8\cdot10^{-6}y^2}\right)e^{-0.09x^2} \quad (3.19)$$

$$\gamma_3(x,y)=8.6\left(1-e^{\frac{-y}{50}}\right)e^{-0.09x^2} \quad (3.20)$$

$$\gamma_4(x,y)=14\left(1-e^{\frac{-y}{50}}\right)e^{-0.46x^2} \quad (3.21)$$

$$\gamma_4(x,y)=5\left(1-e^{\frac{-y}{50}}\right)e^{-0.9x^2} \quad (3.22)$$

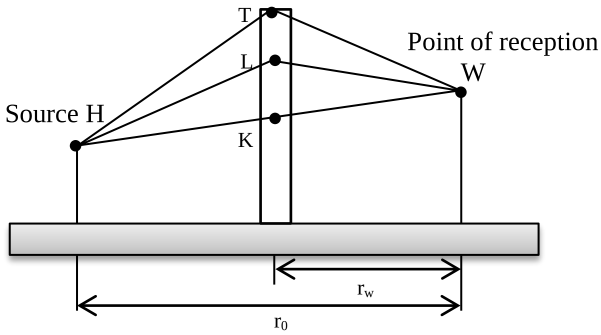
If there is no barrier between source and the point of reception, both S_w and S_h are given value of 1. In case of barrier presence the S_w is found using (3.24) and S_h using (3.25).

If there are objects on the way from source to receiver which interfere with the sound transmission, the screening effect L_{SW} is taken into account. The formula for calculating the attenuation by an object of variable shape contains two factors. The first factor describes the screening by an equivalent idealized barrier (a thin, vertical plane). The height of the equivalent barrier corresponds to the height of the obstructing object. The upper edge of the barrier corresponds to the highest edge of the obstacle.

The second factor is important only if the object profile deviates from that of the idealized barrier. The profile is defined as the cross-section of the sector plane of the attenuating object. The attenuation of the object is equal to the attenuation of the equivalent barrier minus a correction factor C_p depending on the profile. If several attenuating objects are present in a sector, only the object that in the absence of the others would cause the most attenuation is taken into account.

The equations given hereafter are valid for barrier heights up to 4 m, placed not closer than 4.5 m from the center of the track. For other cases the screening effect can be overestimated.

The idealized barrier between source and point of signal reception is shown in 3.2. fig.



3.2. fig. The idealized barrier between source and point of signal reception

In order to calculate attenuation due to an object, the following parameters are taken into account: r_0, m; r_w, m; r – distance between the source and point of reception along the shortest connection line, m; h_h, m; h_w, m; z_h – source height above railhead, m; z_w – reception point height above railhead, m; h_T – height of the upper edge of the idealized barrier relative to the average level in 5 m range around the barrier; object profile.

In 3.2. fig. K represents intersection point of the barrier and the line of sight between source and receiver; L represents intersection point of the barrier and a curved sound ray, that reaches the assessment point from the source point in downwind conditions and T represents the upper edge of the barrier.

If the T, L and K point heights above railhead are Z_T, Z_L and Z_K correspondingly, than the distance between points K and L, m is calculated as follows [25]:

$$Z_L - Z_k = \frac{r_w(r_0 - r_w)}{26 r_0} \tag{3.23}$$

$$S_w = 1 - \frac{r_0 - r_w}{r_0} \frac{3h_e}{3h_e + h_w + 1} \qquad \text{for } h_e > 0 \tag{3.24}$$

$$S_h = 1 - \frac{r_w}{r_0} \frac{3h_e}{3h_e + h_h + 1} \qquad \text{for } h_e > 0, \tag{3.25}$$

where $h_e = Z_T - Z_L$ - the effective barrier height, m.

The attenuation factor L_{SW} is calculated using [25]:

$$L_{SW} = HF(N_f) - C_p, \tag{3.26}$$

where $H = 0.25 h_T 2^{i-1}$ – screening performance factor and i – octave band number; C_p – correction factor depending on the object profile, dB (thesis 12. attachment); $F(N_f)$ – function from Fresnel number N_f, defined in 3.9. table.

The Fresnel number is determined as [25]:

$$N_f = 0.37 \varepsilon 2^{i-1}, \tag{3.27}$$

where ε – acoustic pathway, m.

$$\varepsilon = (HT + TL) - (HL + LW) \qquad \text{for} \qquad Z_T \geq Z_K$$

$$\varepsilon = 2r - (HT + TL) - (HL + LW) \qquad \text{for} \qquad Z_T < Z_K \tag{3.28}$$

3.9. table

Definition of function $F(N_f)$

N_f interval		$F(N_f)$
from	to	
-∞	-0.314	0
-0.314	-0.0016	$-3.682 - 9.288\log_{10}\lvert N_f\rvert - 4.482\log^2{}_{10}\lvert N_f\rvert - 1.170\log^3{}_{10}\lvert N_f\rvert - 0.128\log^4{}_{10}\lvert N_f\rvert$
-0.0016	0.0016	5
0.0016	1	$12.909 + 7.945\log_{10} N_f + 2.612\log^2{}_{10} N_f + 0.073\log^3{}_{10} N_f - 0.184\log^4{}_{10} N_f - 0.032\log^5{}_{10} N_f$
1	16.1845	$12.909 + 10\log_{10} N_f$
16.1845	+∞	25

The reflection effect L_R takes into account the loss of sound energy of the sound ray propagating from source to receiver and is calculated using [25]:

$$L_R = N_{ref} \delta_{ref}, \tag{3.29}$$

where N_{ref} – the number of reflections; δ_{ref} – reflection loss, dB.

$$\delta_{ref} = 10\log_{10}(p), \tag{3.30}$$

where p = 1- α is reflection coefficient and α is absorption coefficient.

The recommended value of δ_{ref} for buildings is 0.8 dB and 1.0 dB for all other objects, unless the object is proven to be sound absorbing.

Due to empirical nature of the RMR method, it is obvious that the applicability of the RMR method in other from Netherland national railway conditions should be evaluated and in case of necessity the new radiation parameters have to be defined [26].

4. EXPERIMENTAL INVESTIGATION OF RAILWAY NOISE

Railway noise modeling is always closely related to railway noise experimental investigations. In many cases it is physically not possible to use only modeling to solve problems related to railway noise. Measurement results always either form the basis for modeling, either are used for modeling result verification or both. Measurements usually provide better information about the situation under consideration, however modeling can be used for predictions.

In order to evaluate the existing acoustical situation on Latvian railway and to verify the applicability of EU recommended RMR method, numerous measurements of pass by noise spectrums of all train types operating on Latvian railway were performed. Of the most importance was the investigation of rolling noise for all train types on railway track with jointless rails, however, the traction noise, braking noise and impact noise was also examined where it was possible. In addition, some long time measurements of equivalent A-weighted noise levels were performed for noise mapping purposes discussed in chapter 5.

Measurement equipment

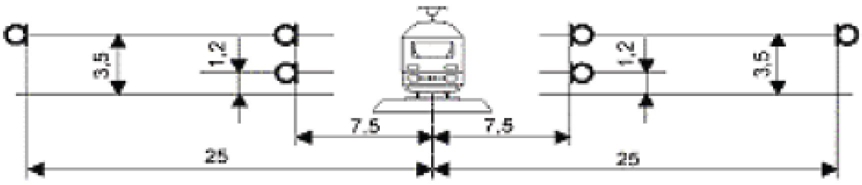
For all measurements the following equipment was used: SVAN 947 sound and vibration analyzer Ser., N. 6862; preamplifier SV12L Ser. N. 10602; microphone SV22 Ser. N. 4012051 and sound level calibrator SV30A Ser. N. 10593. All measurement equipment meets the requirements for class 1 equipment specified in IEC 61672 and IEC 61260.

Measurement conditions

In accordance with ISO 3095 [20] and RMR measurement recommendations, the measurement site must offer free field conditions. The soil must be free of obstacles and there must be no reflecting objects such as walls, buildings, slopes or bridges closer than 3 times the distance between source and receiver. The ground needs to be essentially flat and within a level from 0 to (-1) m relative to the top of the rail. The soil must be as far as possible free of strongly absorbing surfaces such as snow, high grass, or strongly reflecting surfaces such as water.

The measurements shall be made if the wind speed at the microphone height is less than 5 m/s and there is no falling rain or snow.

The microphone position is at the distance of 7.5 m from track center and 1.2 m above railhead. If sources above 0.5 m height have to be considered additional microphone height at 3.5 m must be added, 4.1. fig. [20]

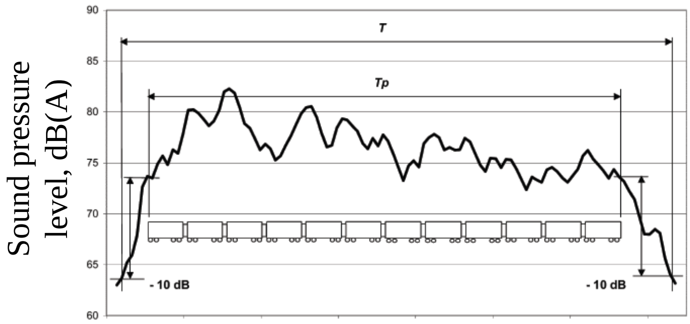


4.1. fig. Microphone position at the test site, distances and heights are in meters

The background noise is measured at least 60 seconds and its levels should be at least 10 dB lower than the measured source level.

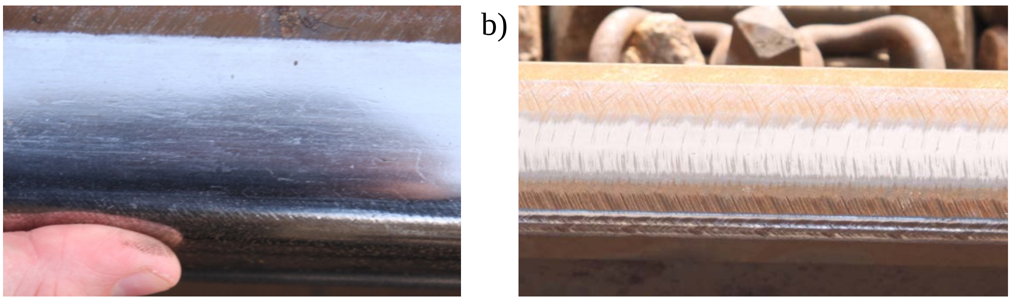
Before and after each measurement session, the whole measurement chain is calibrated. If the difference between two adjacent calibration factors exceeds the value of 0.5 dB, then all measurement results during current session are rejected.

For train pass by noise measurement, the measurement time interval T is chosen, so the measurement starts when the A-weighted sound pressure level is 10 dB lower than found when the front of the train is opposite the microphone position. The measurement is stopped when the A-weighted sound pressure level is 10 dB lower than found when the rear of the train is opposite the microphone position, 4.2. fig. [20]



4.2. fig. Measurement time

Two places were chosen for measurements at the railway line Riga – Aizkraukle. The first measurement place was between two train stations “Dārziņi” and “Dole”, roughly 800 m from station “Dārziņi” in the direction of station “Dole”. The second place was at station “Dole”. These places were chosen due to the following reasons: the environment conditions meet the requirements as far as possible; this railway line is with the most traffic intensity; all operational in Latvia train types can be investigated; at the station it is possible to measure braking noise and noise from accelerating trains; background noise levels were constantly lower than 40 – 45 dB(A) in all octave bands. In addition there were two tracks at this railway line, allowing measurement result comparison. Moreover, these were tracks consisting of the same elements: UIC-60 rails; Vossloh SKL-14 rail fastening system and Vossloh rail pads; concrete monoblock sleepers. The first track was rebuilt in 2003, the second in 2001. The main difference was that the first track was reprofiled by grinding 6 month before measurement campaign and the second – 3.5 years before measurement campaign. This gave a chance to evaluate the effect of rail grinding on rolling noise. Pictures of both track railheads are shown in 4.3. fig. [5]

a)


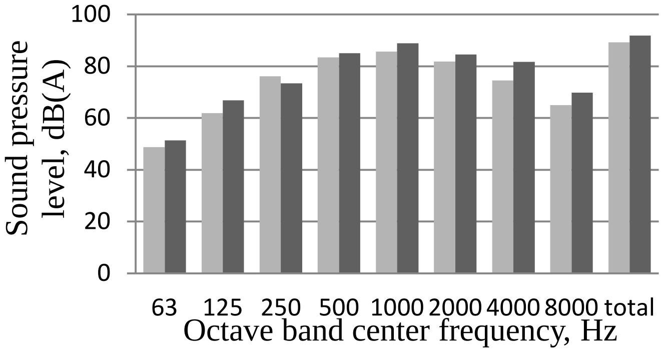
4.3. fig. Pictures of rail rolling surface of both tracks at measurement sites

a, the non-grinded track; b, the grinded track

Here it is important to mention, that the good practice of many European countries is the use of rail grinding for rolling noise reduction, yet, in Latvia the acoustic effect of rail grinding has never been qualitatively evaluated. It can be seen in 4.3. fig. that deep grinding stone signature was left on the rail surface.

It was discovered that pass by noise levels of all train types at all speeds were increased due to poor quality rail grinding in all octave bands. Unfortunately, the test train was not available during measurement campaign, however the correlation between measurement results on two tracks was verified by the electric train pass bys: it was possible to make measurements for the same electric train, passing at the same place and same speed in the same day, but in different directions (different tracks). The examples of electric train pass by noise spectra on both tracks at the speed of 70 km/h are shown in 4.4. fig.

Since measurements were conducted in accordance with ISO 3095 and RMR recommendations, the A-weighted spectrums will be presented hereafter. The low frequency signals are highly attenuated, therefore only octave bands from 63 Hz to 16 kHz will be considered (the highest considered frequency in RMR is 8 kHz).



4.4. fig. Pass by noise level of electric train, dark-grinded, light - non-grinded track

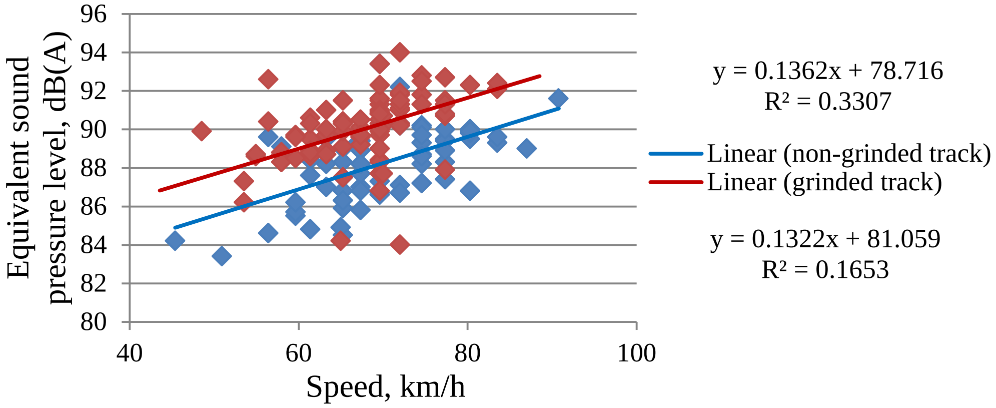
It can be seen that noise levels in the darker spectrum, measured for grinded track, exceed levels measured for other track in all octave bands except 250 Hz. Usually the frequency of 250 Hz is resonant for sleeper vibration. Therefore, increased noise level in this octave band probably points out on loose sleeper, but additional investigation is needed to find the reason. The biggest difference in spectrums in this case is 7.2 dB(A) in 4 kHz octave band. The roughness wavelength for 4 kHz at the speed of 70 km/h is about 5 mm that correspond to the roughness wavelength of the grinding stone signature in 4.3. fig.

The main reason of poor grinding quality usually is the question of cost/quality ratio. To reduce the maintenance cost, the number of grinding machine passages over a track sector is reduced. In order to achieve smoother rolling surface the number of grinding machine passages should be increased with decreasing the passage speed, at least for the last passage. Railway stock on Latvian railway has conical type of wheels and the main attention during the grinding process is paid to this relatively small contact patch area, to increase the grinding speed, the remaining part of railway surface on both sides of the contact area is left even rougher. It has to be taken into account, that the rail surface is worn out with the time and later the wheels will interact with these rough side parts of the rail also and the overall rail and wheel lifespan will be decreased.

This information was included as a part of the report [8] and forwarded to the company, which made the reprofiling work. Reprofiling company will organize survey commission and after the reasons of poor grinding quality will be investigated, the track will be reprofiled free of charge.

Train pass by noise level speed dependencies

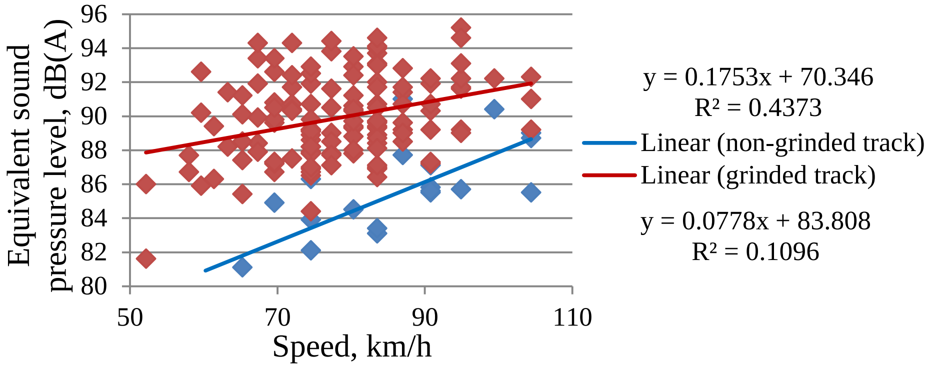
Let us consider the experimentally obtained pass by noise level speed dependencies for all train types on both tracks from 4.3. fig. Equivalent A-weighted noise levels for non-braking trains of each train type were plotted versus speed and the pass by noise level speed dependencies were represented by least squares linear regression lines (LSLRL) using Excel linear regression analysis.



4.5. fig. Electric train pass by noise level speed dependency

In 4.5. fig. the constant difference of 2 dB(A) between noise levels on two railway tracks can be seen in case of electric trains. Doubling the speed from 45 km/h to 90 km/h leads to increase of noise levels by 6 dB(A) for both railway tracks.

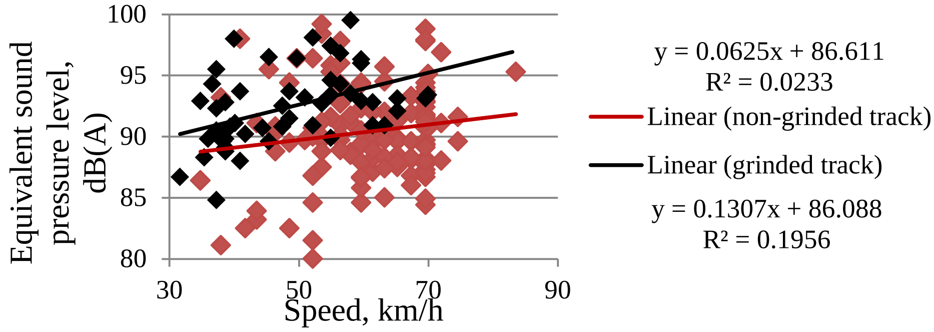
There is bigger difference between pass by noise levels on two different tracks in case of disc-braked diesel passenger trains, 4.6. fig. The increase of speed from 60 km/h to 100 km/h result in increase of pass by noise levels by about 3.5 dB(A) in case of rough track and 7 dB(A) in case of smoother track.



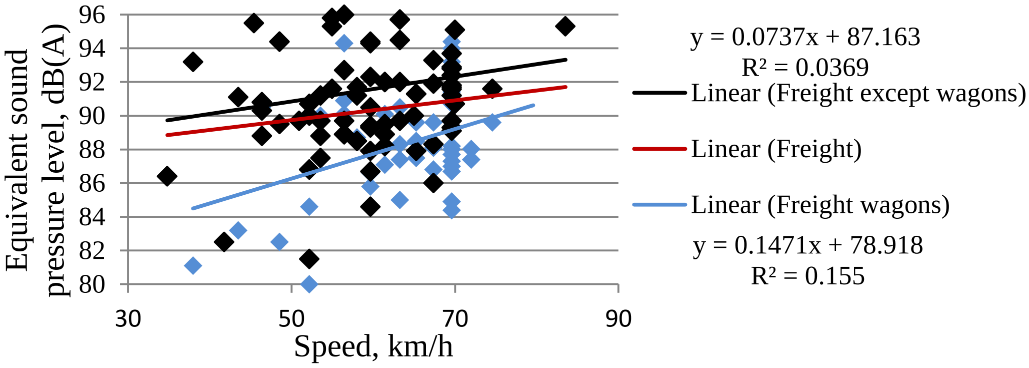
4.6. fig. Diesel passenger train pass by noise level speed dependency

When track roughness dominates over wheel roughness, rolling noise levels for tread-braked and disk-braked trains can be similar. It can be seen in 4.5. and 4.6. figs. that rolling noise levels for diesel and electric trains on grinded track are almost same at the speed of 50 km/h, but at the speed of 90 km/h diesel trains radiate about 2 dB(A) less noise. This difference probably occurs due to rougher electric train wheels. In case of smooth track, the rolling noise levels can vary by approximately 10 dB(A) due to wheel roughness. In particular case, the disc-braked trains with smoother wheels radiate about 5 dB(A) less noise than tread-braked trains at the speed of 90 km/h, 4.10. fig.

Here, the roughness means root mean square value of the amplitude variation of the running surface of a rail (or a wheel) in the direction of motion, measured over a length of a rail (or a wheel), expressed in µm [20].



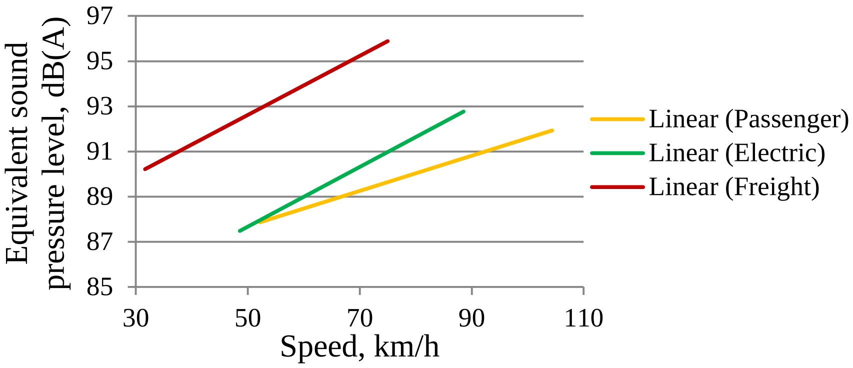
4.7. fig. Freight train pass by noise level speed dependency



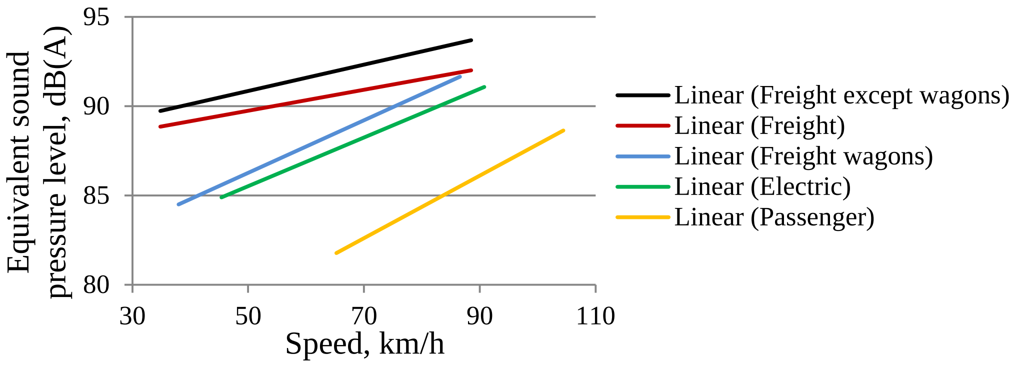
4.8. fig. Pass by noise level speed dependency of freight train subcategories

In 4.7. fig. are shown pass by noise level speed dependencies for freight trains. The increase of speed from 40 km/h to 70 km/h result in increase of pass by noise levels by about 4 dB(A) in case of rough track and 2 dB(A) only in case of smoother track. In 4.7. fig. all freight trains are considered as single category in accordance with RMR description, however during the investigation it was discovered that it is essential to divide freight trains into subcategories in terms of acoustic radiation. At least three subcategories are recommended: freight trains consisting only from wagons; freight trains consisting only from cisterns and mixed freight trains. No sufficient data was available for acoustic description of freight trains consisting only from cisterns yet. The mixed freight train category keeps the same noise level speed dependency as non-categorized freight trains, with increased by 1 dB(A) levels at all speeds. The noise level speed dependency of freight trains consisting only from wagons is similar to that of electric trains with levels higher by about 1 dB(A). This proves the importance of freight train categorization. The difference in noise radiation of freight trains divided in subcategories is more important for the smoother track and is shown in 4.8. fig.

Speed dependencies of all train types with divided into subcategories freight trains in case of smoother track are shown in 4.9. and 4.10. figs [5]. From 4.9. and 4.10. figs. follows that none of the train categories operating on Latvian railway meets the new TSI requirements [28]. It is financially impossible for Latvian railway to retrofit all rolling stocks or to order all new, however the order of new passenger trains was made already. Moreover, main part of freight rolling stock comes from neighboring countries (Russia and Belarus), therefore the special case of limiting noise values for Latvia (and other Baltic states) is currently discussed and results of current research will be used by Latvian railway to evaluate the existing situation in order to propose acceptable for Latvian railway condition recommendations on noise limits.



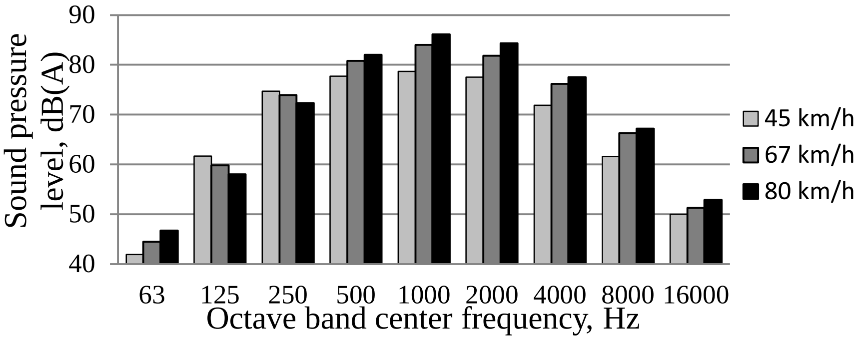
4.9. fig. Pass by noise level speed dependency of trains on grinded track



4.10. fig. Pass by noise level speed dependency of trains on non-grinded track

Train pass by noise spectra analysis

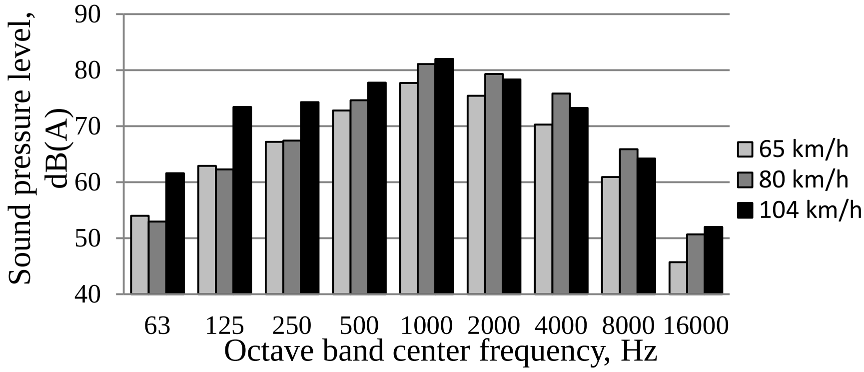
The increased rail surface roughness after grinding in this particular case is not a typical situation for the whole railway network in Latvia, therefore we will mainly consider spectrums of pass by noise for non-grinded and relatively smooth track, assuming such a track as the average track of Latvian railway network. The measurement results being the direct points (or being very close to) of LSLRL in 4.10. fig. were taken for analysis.



4.11. fig. Pass by noise spectrums of electric trains at different speeds

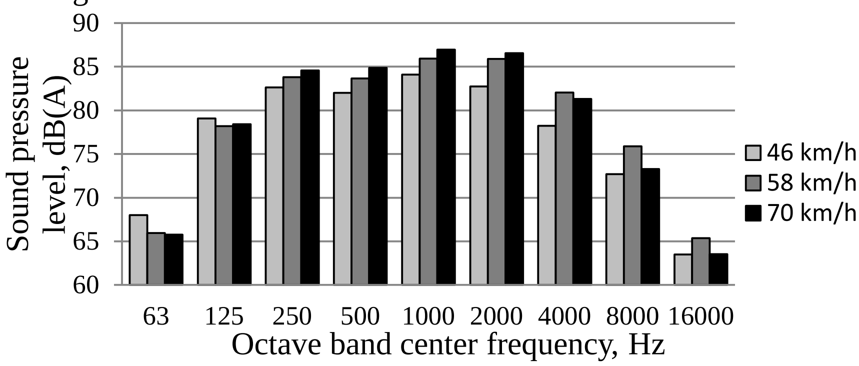
An interesting finding seen in 4.11. fig. is that noise levels in 125 Hz and 250 Hz octave bands are decreasing with increasing speed, this might be described by the low frequency traction noise being louder during train acceleration or by differences between trains. In all other octave bands noise levels have increased with the speed.

In case of diesel passenger trains the noise levels in first three octave bands found to be speed independent at conventional speeds, but at speeds close to maximal the considerable increase at low frequencies occurs which might be due to exhaust and engine noise, 4.12. fig. In other octave bands levels tend to increase with speed, lower levels at high frequencies for the fastest train might be due to differences between trains.



4.12. fig. Pass by noise spectrums of diesel passenger trains at different speeds

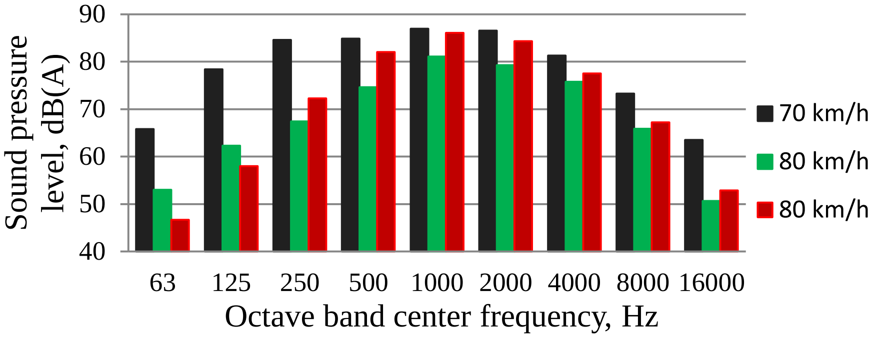
The noise spectrum speed dependency of freight trains is shown on the example of mixed train in 4.13. fig.



4.13. fig. Pass by noise spectrums of freight mixed trains at different speeds

Results for freight trains are hardly analyzable due to possible differences between trains, however it can be clearly seen that the main increase in noise levels with increasing speed found in octave bands from 250 Hz to 4 kHz. Noise levels in 63 Hz and 125 Hz octave bands are not speed dependent not taking into account data for the slowest train (traction noise). At the high frequencies levels tend to increase with speed, except the fastest train.

Spectrums of electric (red) and diesel trains (green) at speeds of 80 km/h and mixed freight train (black) at the speed of 70 km/h are combined in 4.14. fig.



4.14. fig. Pass by noise spectrums of different trains

black – freight train, green – diesel passenger train, red – electric train

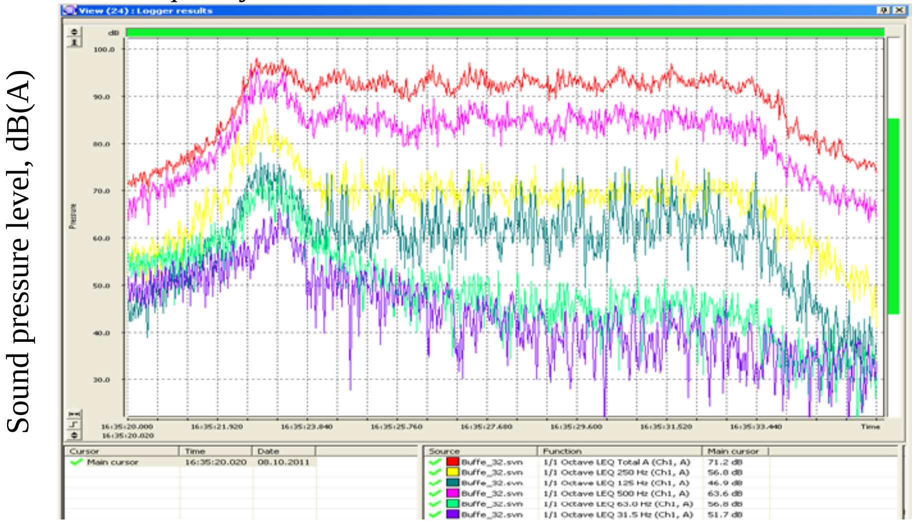
It can be seen that measured sound pressure levels in 4 kHz, 8 kHz and 16 kHz octave bands are similar for diesel passenger and electric trains. Diesel trains radiate less noise in the middle frequency range, but have higher levels at low frequencies, 4.12. fig. The mixed freight trains even at lower speed radiate higher noise levels in all frequency octave bands compared to other train types. The main part of low frequency radiation belongs to freight trains. This must be due to higher dynamic forces during freight train pass by, causing increase in noise radiation by rails and sleepers. The freight train wheels also expected to be the roughest. No doubt that freight trains cause high level of the ground born vibrations which together with the radiated low frequency noise can propagate over long distances with a very little attenuation. It was discovered during current research that many of the empty freight trains radiated less noise, although it is hard to talk about the direct dependency of the radiation level on the train weight because of the low-correlated results.

Another feature of freight train noise radiation is the high deviation between noise levels radiated by different wagons within a single train, 4.15. fig. Such a high dynamic range of the freight train noise radiation makes it very annoying. The “annoyance” is not regulated by any standards, but it is found that the source with changing in time radiation intensity causes more disturbances compared to the source with constant radiation even with the higher level. This fact should be taken into account during train time table planning, especially for the night period of time.

4.15. fig. Freight mixed train pass by noise level, dB(A) in the time domain

Traction noise

The traction noise of electric trains is hardly detectable, because it is masked by the rolling noise. The traction noise is well seen in case of diesel passenger train and freight train locomotives. In 4.16. fig. are shown sound pressure levels of diesel passenger train pass by noise in low frequency bands and the total A-weighted levels. It can be seen that at the beginning of the measurement (left side) when the locomotive is opposite the microphone, the sound pressure levels in 31.5 Hz, 63 Hz, 125 Hz, 250 Hz and 500 Hz are higher compared to other part of rolling stock (10 wagons, at the speed of 84 km/h). Freight train locomotives have high level of low frequency traction noise in the 63 Hz octave band.



4.16. fig. Pass by noise levels of diesel passenger train in the time and frequency domain

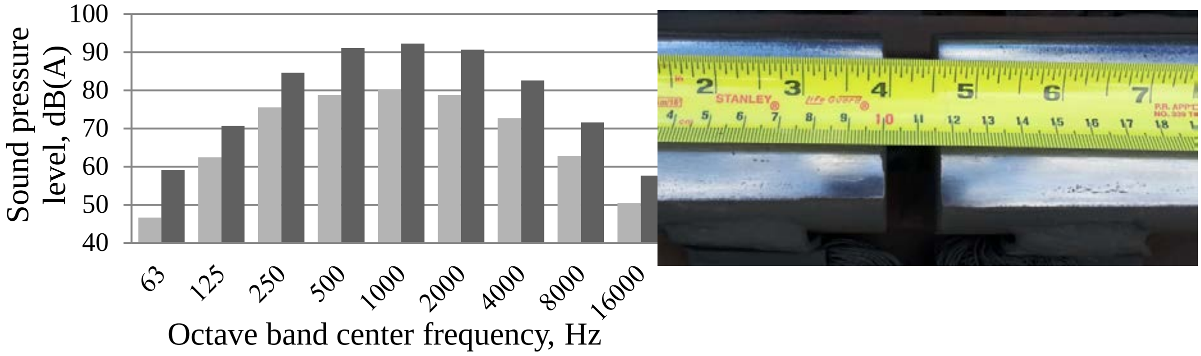
Braking noise

The braking noise was measured for electric passenger trains stopping at the train station. It was discovered, that the occurrence of high level tonal squeal noise is strongly dependent on the braking intensity. It is possible to stop the train without any noticeable increase in the noise levels if the low braking force is applied in a due time. In 4.17. fig. an example of electric train high level tonal braking squeal noise is seen in the 8 kHz octave band, increasing the total noise level by about 10 dB(A). In some cases the main noise level increase is found in 4 kHz and 16 kHz octave bands. In case of European tread-braked rolling stock the braking squeal noise occurs mainly in the 4 kHz octave band.

4.17. fig. Electric train braking noise levels in time and frequency domain

Rail joint impact noise

Each rail joint have a gap between two jointed rails. The increase in rolling noise level is strongly dependent on the width of the gap between rails and the difference in heights between rolling surfaces of jointed rails. The problem is that due to physical laws and railway maintenance instruction joint geometrical parameters (gap width can change from 0 mm to 31 mm) can change in time. Thus, the impact noise at rail joints should be investigated in each case separately. In 4.18. fig. is shown example of the electric train pass by noise level increase in all octave bands with the total level increase by about 12 dB(A) due to rail joint. [7, 8]

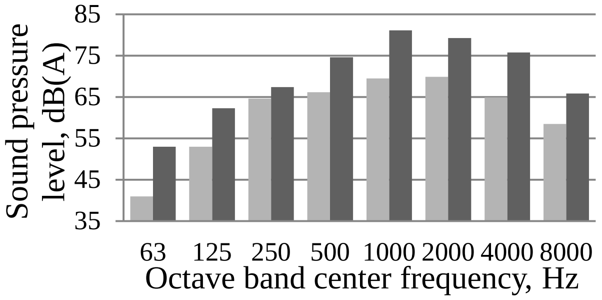


4.18. fig. Electric train pass by noise spectrums, dark – rails with joint; light – jointless rails

Comparable analysis of experimental investigation and modeling results using RMR method

At the beginning of this work, for simple cases, the numerical calculations following RMR method description were performed in MathCAD, but later within projects co-financed by Latvian railway the CadnaA noise mapping software was bought by Institute of railway transport. In addition, the software for spectrum calculation in the point of reception using RMR octave band method - Train Noise Software (TNS) was developed by author and was used for CadnaA calculation result evaluation and improvement of the RMR method for specific conditions of Latvian railway. Let us first compare experimental investigation results with CadnaA modeling results. The measurement results being the direct points (or being very close to) of LSLRL in 4.10. fig. were taken for analysis.

In 4.19. – 4.20. figs. correspondingly are shown measured and calculated using CadnaA spectrums for diesel passenger train, electric train, freight train consisting only from wagons and mixed freight train, assuming that the ground absorption factor is equal to 0.5. [5]



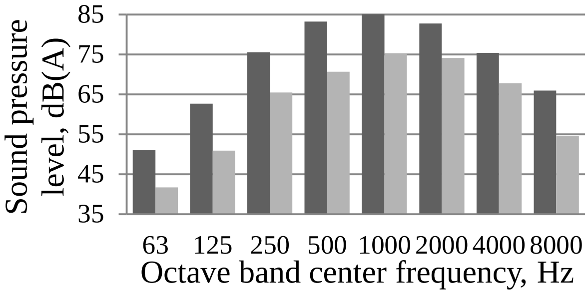
4.19. fig. Measured (dark) and CadnaA calculated (light) spectrums of diesel passenger train pass by noise

train speed - 80 km/h, measurement time - 5.7 s, RMR train type category 6

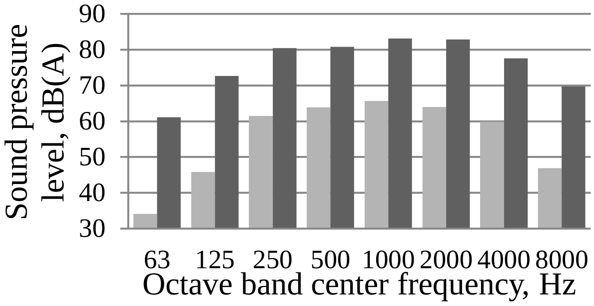
The measured noise levels are higher than calculated in all octave bands by 2.8 dB(A) (250 Hz) – 11.6 dB(A) (1 kHz). The total difference is 9.8 dB(A).

The maximum in measured spectrum is in 1 kHz octave band, while in calculated spectrum it is in 2 kHz. There is no low-frequency engine noise peak in measured spectrum at 250 Hz as in calculated spectrum. If the RMR train type category for diesel passenger train with engine noise is used for modeling, the difference in total noise levels is decreased by 3 dB(A), but spectra shape lines differ more due to calculated low-frequency and 2 kHz peaks being even more expressed. As follows from 4.12. fig. the engine noise correction is essential for Latvian diesel passenger trains, only at higher speeds and at lower frequencies.

The measured noise levels of electric trains in 4.20. fig. are higher than calculated in all octave bands by 7.6 dB(A) (4 kHz) – 12.6 dB(A) (500 Hz). The total difference is 10.3 dB(A). The difference between calculated and measured electric train total noise levels is only 0.5 dB(A) more than in diesel passenger train case. The calculated spectrum shape shows to be a good fit to measurement results.

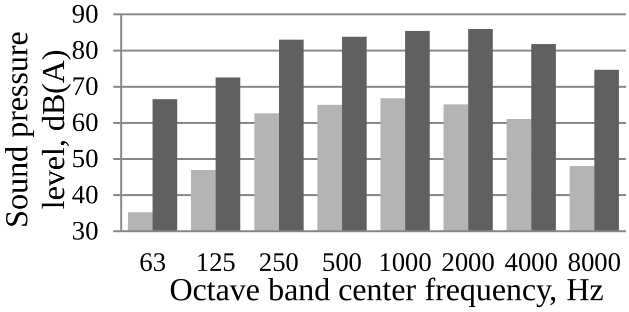


4.20. fig. Measured (dark) and CadnaA calculated (light) spectrums
of electric train pass by noise
train speed - 77 km/h, measurement time - 5.9 s, RMR train type category 1



4.21. fig. Measured (dark) and CadnaA calculated (light) pass by noise
spectrums of freight train consisting only from wagons
train speed - 65 km/h, measurement time – 46.5 s, RMR train type category 4

The measured noise levels are higher than calculated in all octave bands by 17.4 dB(A) (1 kHz) – 27.1 dB(A) (63 Hz). The total difference is 18 dB(A). Biggest difference in first two octave bands must be due to traction noise and higher axle load. There is no peak in 2 kHz octave band in the calculated spectrum.

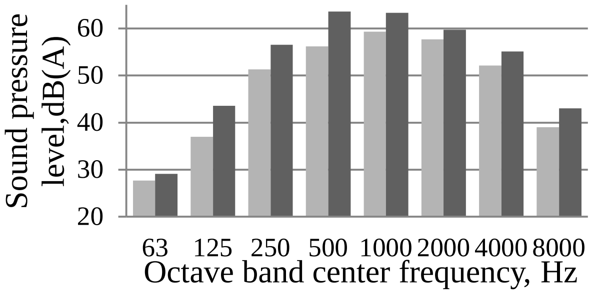


4.22. fig. Measured (dark) and CadnaA calculated (light) spectrums
of mixed freight train pass by noise
train speed - 65 km/h, measurement time – 36.5 s, RMR train type category 4

The measured noise levels are higher than calculated in all octave bands by 18.6 dB(A) (1 kHz) – 31.3 dB(A) (63 Hz). The total difference is 19.7 dB(A).

In general, calculated noise spectra shape lines follow measured spectra shape lines precisely enough, but noise levels are underestimated in all octave bands. As expected, the biggest difference between measured and calculated noise levels is in case of freight trains. The lowest difference between total calculated and measured equivalent A-weighted noise levels found to be in case of diesel passenger trains.

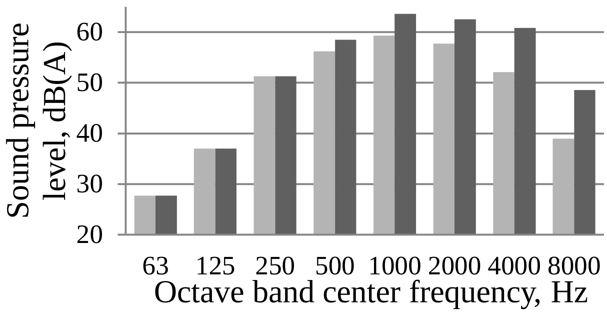
Another important finding is linked to the RMR feature - calculated noise levels are traffic intensity dependent, but not directly train length dependent. Let us compare calculated freight train spectrums in 4.21. and 4.22. figs. The only change in calculations is the traffic intensity depending on the measurement time (train length). In real situation, the measurement time does not affect the measured equivalent sound level value of a single statistically constant source. But due to empirical RMR method character, we get different spectrums for different measurement times. Now compare calculated spectrums for freight trains with spectrums for electric and diesel passenger trains - predicted noise levels for freight trains are lower than predicted noise levels for electric and passenger trains. Freight trains are longer, thus, having longer pass by time resulting in lower number of trains (lower traffic intensity) used in calculation comparing to electric and passenger trains. This is not true for a real case, 4.9. and 4.10. figs.



4.23. fig. Pass by noise spectrums, track with joints (dark) and jointless track (light)
electric train, train speed 60 km/h, pass by time 7.2 s

For pass by noise level increase calculation due to rail joints RMR provides correction coefficients for track with jointed rails. These correction coefficients were obtained empirically for tracks and trains of Dutch railways. In 4.23. fig. are shown CadnaA calculated electric train pass by noise spectrums for jointless and track with joints. It can be seen that the main predicted increase is in low frequency range only. [7, 8]

The braking noise in RMR is train type, speed and traffic intensity dependent. The CadnaA calculated increase in noise levels due to electric train braking is shown in 4.24. fig.



4.24. fig. CadnaA calculated pass by noise spectrums for braking (dark) and non-braking (light) electric train
train speed 60 km/h, pass by time 7.2 s

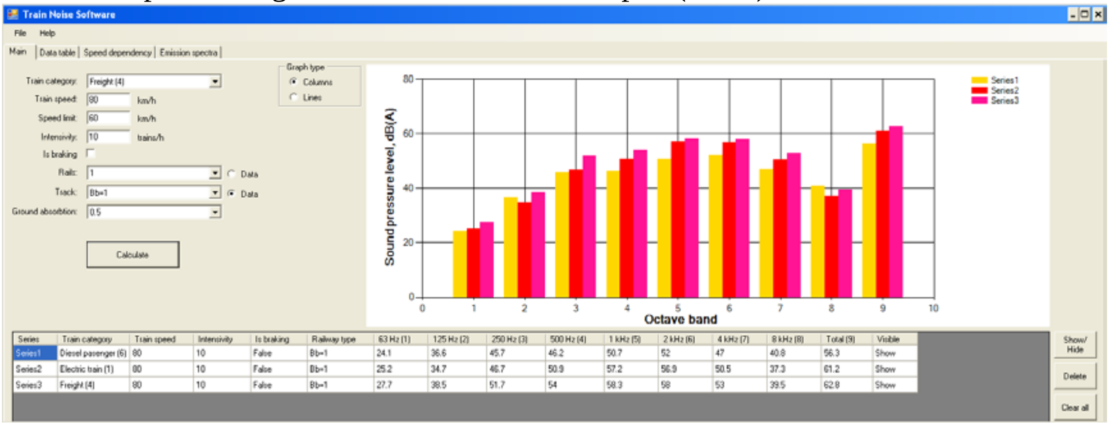
In this particular case, the total level is increased by 4.5 dB(A) as in case with rail joints, but due to level increase at high frequencies. Latvian electric trains may be stopped without considerable increase in noise levels, however if the braking squeal occurs, the main level increase is found in 4 kHz, 8 kHz and even 16 kHz octave bands. The correction coefficients can be redefined for 4 kHz and 8 kHz octave bands, but the 16 kHz octave band is out of RMR area of interest. [7, 8]

Improvement of RMR method for Latvian railway conditions

As follows from train pass by noise spectra modeling and measurement result comparison and [1, 2, 4], the application of the RMR method for railway noise modeling on Latvian railway without appropriate improvement will result in significant underestimation of pass by noise levels in all octave bands of all train type categories and in any conditions.

Here, the improvement means the definition of new radiation index and correction coefficient tables for new train types and tracks. This is currently a very complex problem because the roughness of wheels and rails is not known. However, new types of Latvian trains and track to be used in RMR can be defined statistically using results of current research.

Unfortunately, none of the currently available on the market noise mapping software packages known by author offers user the possibility of new train and track definition for RMR method. To define new train and track categories for Latvian railway, the software, hereafter regarded as Train Noise Software (TNS) for train pass by noise spectrum calculation in the point of reception using RMR method was developed (in C#).



4.25. fig. TNS GUI - pass by noise spectra calculation

The application has a simple and user friendly interface with three main options: total noise level and spectra calculation in the point of reception, noise level speed dependency visualization in all octave bands and radiation spectra calculation. Calculations are based on input data defined in RMR: train type, train speed, number of trains per hour, braking or non-braking operation, track type and rail disconnection class. All radiation indexes, correction coefficients and other required data is stored in the external excel table where the application takes it from. The used data can be viewed within the application. If any data should be changed or added it can be done easily updating the excel table. The example of TNS graphic user interface is shown in 4.25. fig.

Results of TNS calculations found to be in the range of 1.2 dB(A) in each octave band compared to CadnaA calculation results for a reference point at the distance of 7.5 m from the track center and 1.2 m above the railhead for the case of fully absorptive ground, 4.1. table. In the case of fully reflective ground the difference between TNS and CadnaA calculation results in some individual octave bands is increased up to 2.6 dB(A), 4.2. table, however this does not considerably affect the difference in total levels, because of the applied A-weighting function.

4.1. table

Comparison of TNS and CadnaA calculation results, fully absorptive ground

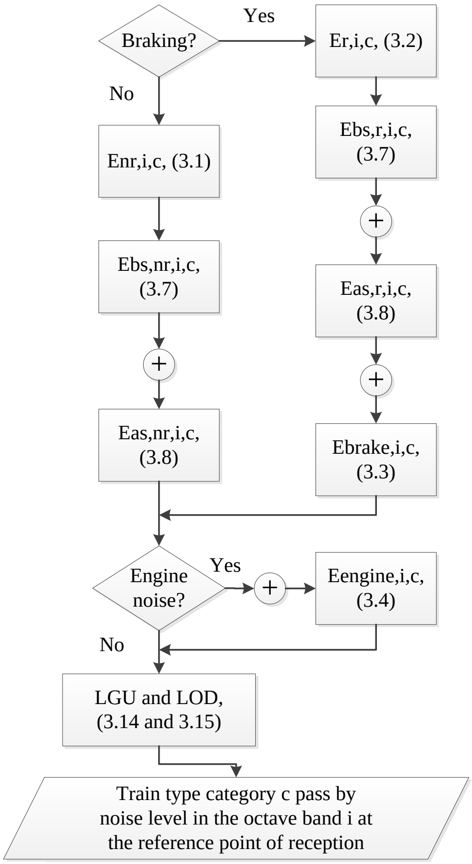
Train type	Octave band center frequency, Hz								
	63	125	250	500	1000	2000	4000	8000	Total
Electric	1.1	1.1	1.2	1.2	1.1	1.1	1.1	1.2	1.1
Diesel	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.2	1.1
Freight	1.0	1.1	1.1	1.1	1.1	1.1	1.1	1.2	1.1

4.2. table

Comparison of TNS and CadnaA calculation results, fully reflective ground

Train type	Octave band center frequency, Hz								
	63	125	250	500	1000	2000	4000	8000	Total
Electric	1.1	2.6	1.4	0.7	0.7	1.1	1.1	1.2	0.9
Diesel	1.1	2.6	1.4	0.7	0.8	1.1	1.1	1.2	1.0
Freight	1.0	2.6	1.4	0.5	0.7	1.1	1.1	1.2	0.9

In 4.26. fig. is schematically shown calculation algorithm for train type category c pass by noise level in the octave band i at the reference point of reception. Calculation is repeated for each of eight octave bands and the total equivalent noise level is found as energetic summation of calculated noise levels in all octave bands. Current version of TNS is used for calculation result comparison with results of measurements performed under RMR recommended conditions, therefore some parameters are precalculated, such as: L_{GU} – the attenuation due to distance, (3.14); D_L – attenuation due to air absorption, (3.16); C_M – meteorological correction factor, (3.17). The difference in ground effect for two source heights found to be relatively small and is neglected. The shortest paths from sources to receiver point are considered to be equal to horizontally measured distance between source and receiver point. The effects of screening L_{SW} and reflection effects L_R are not considered.



4.26. fig. TNS calculation algorithm

Definition of new types of Latvian trains for RMR method

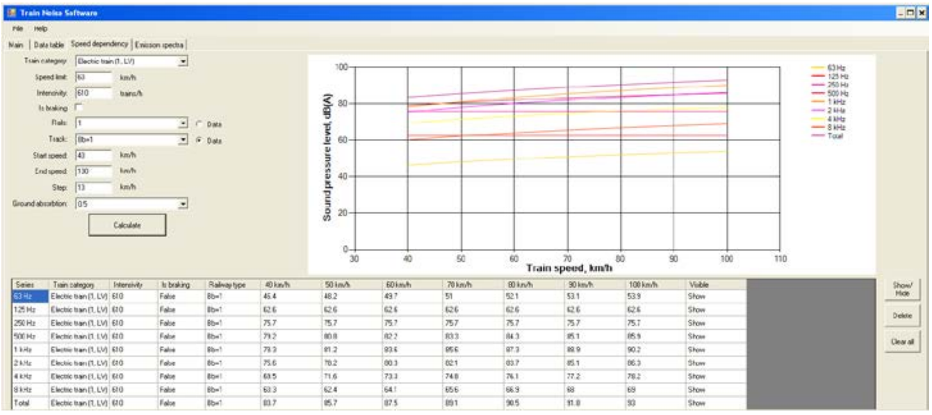
It should be noted, that RMR method is typically used for noise mapping purposes, where the averaged over a long period of time radiation values are estimated, rather than for pass by noise estimation from a single train, therefore calculation results should be compared with statistically averaged measurement results. Using the TNS we will define radiation index table for new train types, taking into account main features of octave band noise level speed dependencies shown in 4.11. – 4.13. figs. and assuming that the ground absorption factor is equal to 0.5.

For the case of electric trains we will assume, that the noise levels in 125 Hz and 250 Hz octave bands are not speed dependent. Noise levels in other octave bands are speed dependent. First we find the N values for each octave band using (4.1) and the known increase in noise levels due to train speed increase from 45 km/h to 80 km/h, 4.11. fig. and then using TNS find the appropriate radiation index a [24], so that TNS calculated spectrum fits experimentally measured in 4.20. fig. The updated values of a and b [24] radiation indexes for

Latvian trains are listed in 4.3. table (train category 1). The TNS calculated noise level speed dependency in octave bands is shown in 4.27. fig. It can be seen that the total noise level speed dependency shows to be a good fit to that experimentally obtained in 4.10. fig.

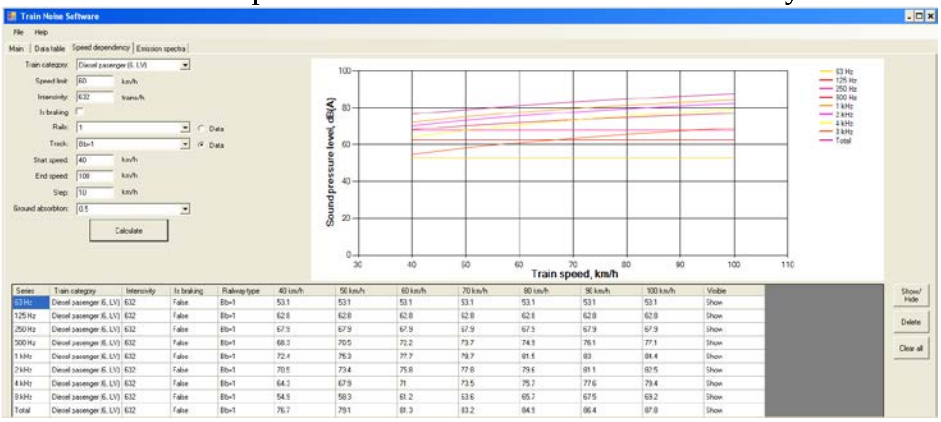
$$L = L_{p0} + N \log_{10}(V / V_0), \tag{4.1}$$

where L – A-weighted sound pressure level, dB(A); L_{p0} – A-weighted sound pressure level at reference speed V_0, dB(A); V – train speed, km/h; V_0 – reference train speed, km/h; N – constant value.



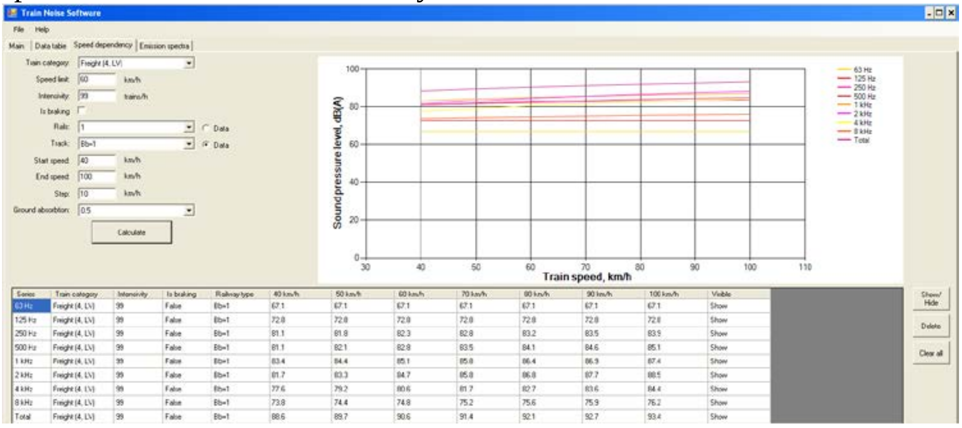
4.27. fig. TNS calculated Latvian electric train pass by noise level speed dependency

For the case of diesel passenger trains we will assume, that the noise levels in 63 Hz, 125 Hz and 250 Hz octave bands are not speed dependent. Noise levels in other octave bands are speed dependent. In a similar manner it was done for electric trains, the a and b radiation indexes are defined, using the known increase in noise levels due to train speed increase from 65 km/h to 80 km/h and 104 km/h, 4.12. fig. TNS calculated spectrum is compared with the one experimentally measured in 4.19. fig. The updated values of a and b radiation indexes for Latvian trains are listed in 4.3. table (c = 6). The TNS calculated noise level speed dependency in octave bands is shown in 4.28. fig. It can be seen that the total noise level speed dependency shows to be a good fit to that experimentally obtained in 4.10. fig. The effect of traction noise at the speeds close to maximal is not considered yet.



4.28. fig. TNS calculated Latvian diesel train pass by noise level speed dependency

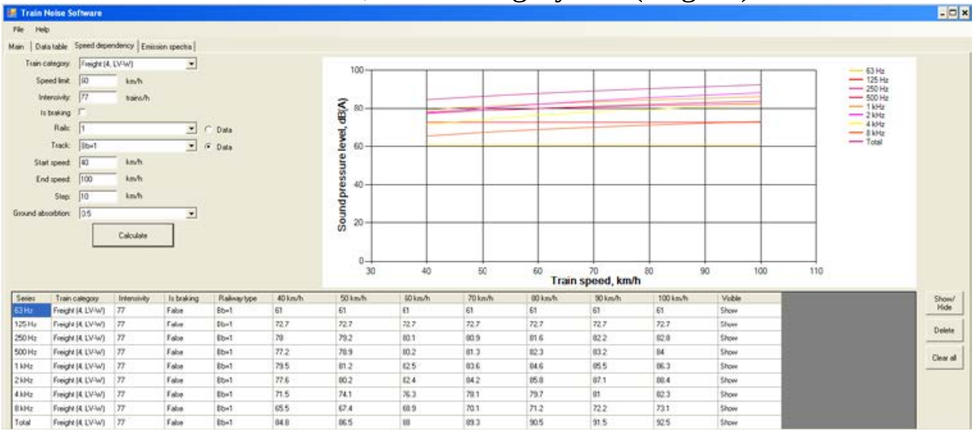
For the case of mixed freight trains we will assume, that the noise levels in 63 Hz and 125 Hz octave bands are not speed dependent. Noise levels in other octave bands are speed dependent. The a and b radiation indexes are defined, using the known increase in noise levels due to train speed increase from 46 km/h to 58 km/h and 70 km/h, 4.13. fig. TNS calculated spectrum is compared with the one experimentally measured in 4.22. fig. The updated values of a and b radiation indexes for Latvian trains are listed in 4.3. table (c = 4). The TNS calculated noise level speed dependency in octave bands is shown in 4.29. fig. It can be seen that the total noise level speed dependency shows to be a good fit to that experimentally obtained in 4.10. fig. The low frequency traction noise of freight locomotives accelerating from low speeds is not taken into account yet.



4.29. fig. TNS calculated Latvian mixed freight train pass by noise level speed dependency

The speed dependency for freight trains except trains consisting only from wagons is similar to mixed freight trains, but with increased radiation levels by about 1 dB(A), 4.3. table category 4NW (non-wagons).

For freight trains consisting only from wagons the radiation levels and speed dependency is different from other freight trains and is shown in 4.30. fig. The radiation indexes a and b are listed in 4.3. table, under category 4W (wagons).



4.30. fig. Pass by noise level speed dependency of Latvian freight trains consisting only from wagons, calculated using TNS

4.3. table

Radiation indexes a and b for five train categories in eight octave bands

Train category c	Radiation index	Octave band center frequency, Hz and number i							
		63	125	250	500	1000	2000	4000	8000
		1	2	3	4	5	6	7	8
1	a	29	80	95	72	49	50	52	43
	b	19	0	0	17	30	27	22	22
4	a	88	98	97	93	94	80	76	90
	b	0	0	7	10	10	17	17	6
4NW	a	90	100	98	94	95	81	77	91
	b	0	0	7	10	10	17	17	6
4W	a	83	99	87	79	80	61	55	62
	b	0	0	12	17	17	27	27	19
6	a	66	80	87	53	43	40	21	15
	b	0	0	0	22	30	30	38	36

Following RMR method description, it is needed to define track correction coefficients $C_{bb,i}$ [24, 25] to take into account the increased roughness compared to non-grinded track. However, in 4.9. and 4.10. figs. we can see that increase in pass by noise levels is different for different train types, therefore it is not possible to define $C_{bb,i}$ common for all train types as in RMR. For freight and diesel passenger trains the radiation level speed dependencies also are different for two tracks. Assuming this is not a usual case for Latvian railway network, the radiation indexes and correction coefficients were not defined for the grinded track yet. The influence of braking and impact noise will be considered within the upcoming research project initiated by Latvian railway [10].

5. RAILWAY NOISE MAPPING

Noise map is the representation of calculated noise levels in two or three dimensions for the area of interest. In accordance with 2002/49/EC directive on environmental noise, strategic noise maps had to be prepared for agglomerations with 250000 inhabitants before 30.06.2005, for agglomerations with 100000 inhabitants and major railway lines with more than 30000 train passages per year before 30.06.2012. Prepared strategic noise maps should be updated every five years.

On the territory of Latvia in accordance with [23] listed in 5.1. table limiting noise level values are applied.

5.1. table

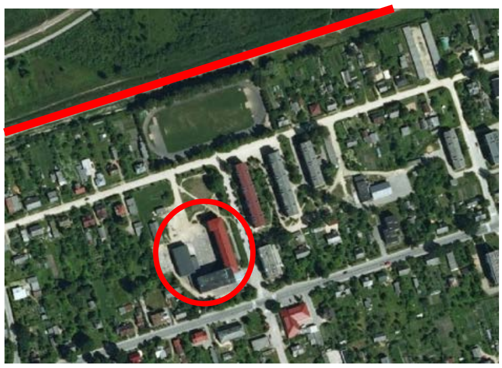
Environmental noise limiting levels

N	Area function	Limiting noise levels, dB(A)		
		L_d	L_e	L_n
1	residential areas with detached houses, areas with hospitals, children and social care authorities as well as resort areas	50	45	40
2	residential areas, areas with culture, education, public administration and scientific authorities	55	50	45
3	areas with multifunctional buildings	60	55	45
4	business areas, areas with hotels, public authorities, sporting territories as well as trading and services zones	60	55	50

If the noise mapping results show that inhabited areas are influenced by noise with levels exceeding those in 5.1. table, the strategic noise reduction action plans have to be developed and implemented by corresponding institutions. Noise reduction and abatement may include different measures discussed in chapter 6. In chapter 6 are also discussed key points of strategic noise reduction action plan developed for Latvian railway.

Noise mapping results on Latvian railway

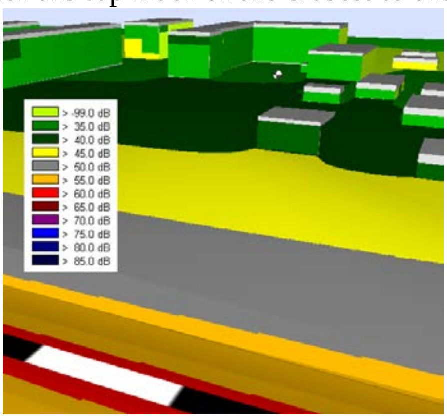
Within the financed by Latvian railway project [8] the noise map for the area of Plavinas gymnasium, 5.1. fig. was developed. Educational institutions such as schools, institutes and universities are very sensitive to exposure of high noise levels, especially during daytime when main part of lessons and lectures take place. It becomes considerably more difficult for pupils and students to acquire new information in noisy environment. Sometimes it becomes even impossible to continue lessons if the school is close to road or railway line [6]. In this particular case the gymnasium is situated at the distance of about 153 m from the railway track center, marked in red in 5.1. fig. The attentions to this object was paid because of the planned reconstruction on the railway network with second line being build next to the existing one. It was decided to prepare the noise reduction plan to be implemented together with the reconstruction work.



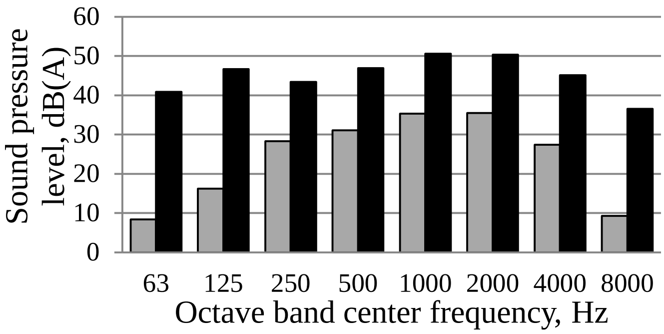
5.1. fig. The area of Plavinas gymnasium

To evaluate the current noise situation, the 12 hour long measurement was performed by author next to the gymnasium. During measurement period, 23 freight trains with average speed of 60 km/h and 20 diesel passenger trains with average speed of 70 km/h have passed well representing the average traffic intensity of this railway line.

Using the known gymnasium dimensions and with the help of GPS measurements the digital area model was manually created in CadnaA. In 5.2. fig. the part of the digital model is shown in 3D view with already calculated noise levels using RMR method and above train traffic information. The track is seen at the bottom as black and white line, the grey and white ball represents the reference measurement point. Different colors correspond to different sound pressure levels with the step of 5 dB(A), the color – level legend is shown in fig. The horizontal grid was calculated for the height of 4 m. the ground absorption factor was set equal to 0.5, buildings were assumed reflective (1 dB(A) reflection loss). It can be seen, that according to RMR calculations, the maximum noise level at gymnasium facade is less than 45 dB(A) (actual value is 41 dB(A) for the top floor of the closest to the railway facade).



5.2. fig. CadnaA noise map of Plavinas gymnasium area in 3D view calculated using RMR method and traffic intensity data

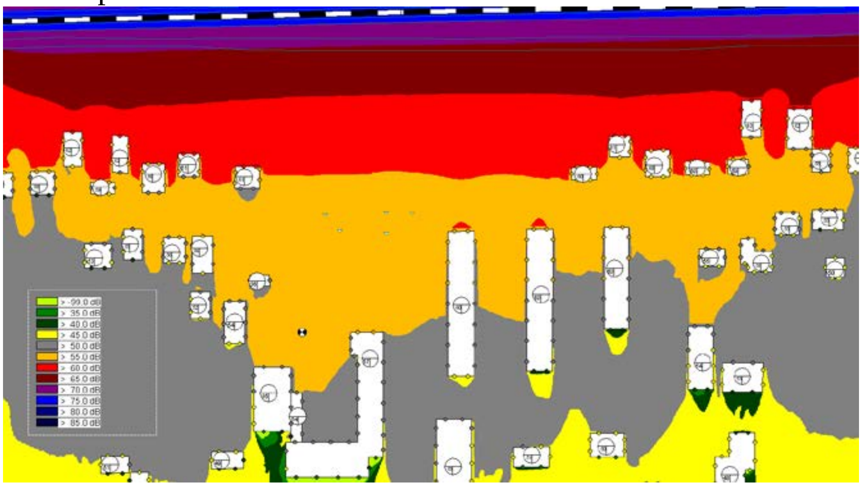


5.3. fig. CadnaA calculated (light) and measured (dark) noise spectrums at the reference point of reception near Plavinas gymnasium

As it was discussed in chapter 4, the RMR method provides incorect results for Latvian railway conditions. It can be seen from 5.3. fig., where the A-weighted measured (dark) and calculated (light) noise spectrums are shown for the reference point of reception.

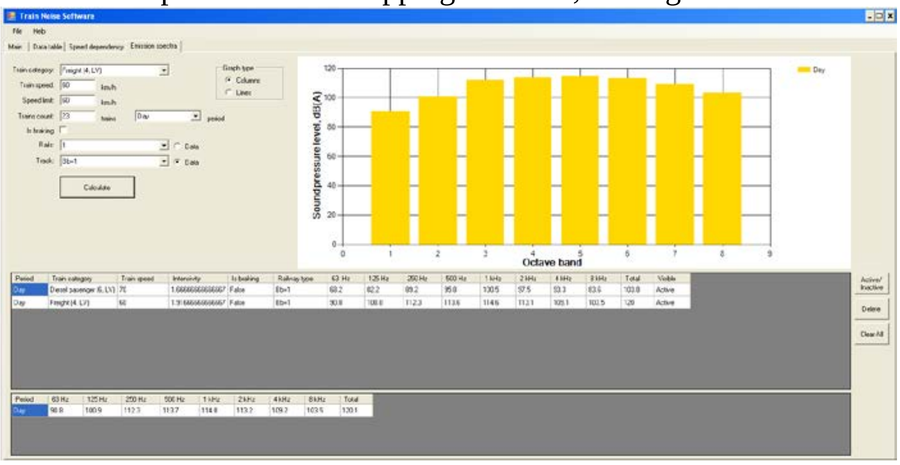
As expected, measured noise levels exceed calculated in all octave bands. The difference is from 15.1 dB(A) in 250 Hz octave band to 32.5 dB(A) in 63 Hz octave band. The total A-weighted equivalent level is underestimated by 16 dB(A). Here it is important to mention that so high low frequency levels are not typical even for freight trains, 4.13. fig. Such high levels in 63 Hz and 125 Hz octave bands can be described by unwanted background noise. It was a town birthday that day and celebrations together with loud music started afternoon. The celebration place was far away from the measurement place, but the low frequency sound waves from powerful acoustic systems could reach the microphone.

At that project stage the TNS was not yet developed and the noise map in 5.2. fig. was updated using measurement results. The updated noise map in 2D view is shown in 5.4. fig. The maximum noise level on gymnasium facade after noise map update is 57 dB(A) and is still only 2 dB(A) above the allowed limit, 5.1. table, but taking into account the increased traffic intensity after the second railway line is built, the noise reduction measures are still essential. The proposed recommendations for noise reduction in this particular case are discussed in next chapter.



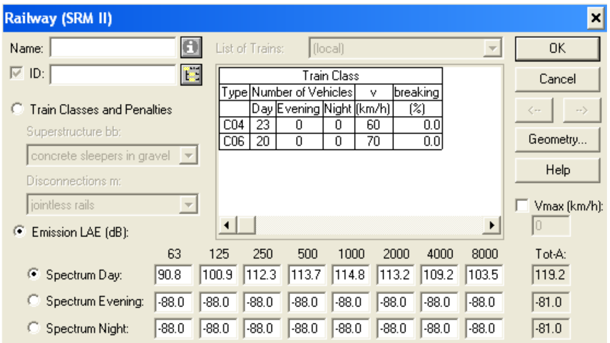
5.4. fig. CadnaA noise map of Plavinas gymnasium area in 2D view calculated using RMR and updated based on measurement results

It is stated in 2002/49/EC directive that strategic noise map has to be developed using modeling, not measurement results. Now it is possible to use the developed TNS software for such problem solving. First the radiation spectrum is calculated using TNS, 5.5. fig. and then used as the source description in noise mapping software, 5.6. fig.



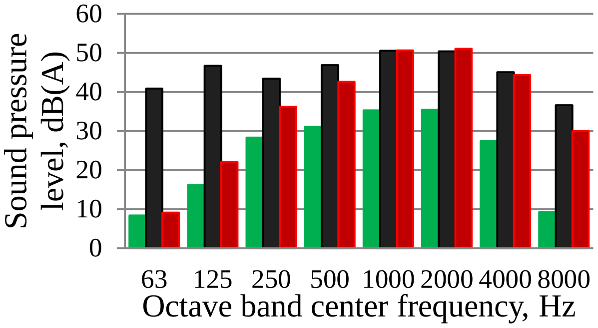
5.5. fig. TNS calculated radiation spectrum

It can be seen in 5.5. fig. that freight train (mixed wagons) radiated noise levels are considerably higher than diesel passenger train radiated noise levels in all octave bands, thus the total radiation spectrum is solely based on the freight train radiation. The maximum impact of diesel passenger trains in total radiation spectrum is 0.2 dB(A) in 1 kHz octave band and therefore can be neglected. This points out again on the fact, that freight trains make the most impact in the total equivalent noise level.



5.6. fig. TNS calculated radiation spectrum used as input data for CadnaA calculations

In 5.7. fig. are shown three spectrums, for both spectrums from 5.3. fig.: green – CadnaA calculated spectrum, using RMR method and traffic intensity data; black – measured spectrum and red – CadnaA calculated spectrum using the TNS precalculated radiation spectrum.



5.7. fig. CadnaA calculated and measured spectrums

The remaining difference in noise levels at low frequency bands between measured and calculated spectrums (TNS precalculated radiation) proves that this was not the railway related radiation. For easier comparison, both spectrums are listed in 5.1. table, TNS-CadnaA calculated spectrum N=1 and measured N=2.

5.2.1. table

Measured and TNS-CadnaA calculated spectrum comparison

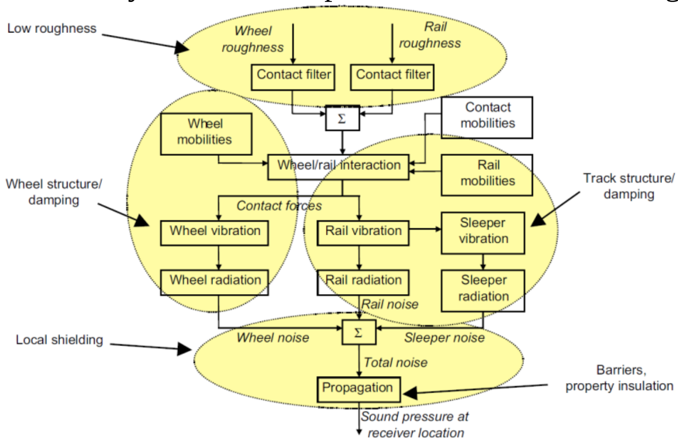
N	Octave band center frequency, Hz								
	63	125	250	500	1000	2000	4000	8000	total
1	9.1	22.1	36.2	42.6	50.7	51.1	44.3	30	54.9
2	40.9	46.7	43.4	46.9	50.6	50.4	45.1	36.6	55.8
1-2	-31.8	-24.6	-7.2	-4.3	0.1	0.7	-0.8	-6.6	-0.9

It can be seen that in 1 kHz and 2 kHz octave bands where peaks found in freight train radiation, 4.13. fig., the level difference is minimal, resulting in less than 1 dB(A) difference in total levels. This proves the correctness of made in chapter 4 assumption that non-grinded track can be treated as the average track of Latvian railway network (the track conditions at Plavinas were similar to the non-grinded track described in chapter 4). This also proves that it is possible to develop the correct noise map for Latvian railway conditions, using the TNS precalculated noise radiation spectrum as source spectrum in noise mapping software.

6. NOISE SOURCE REDUCTION AND NOISE ABATEMENT

The noise mitigation measures can be divided in three categories: noise source reduction – measures at the source to reduce the radiation levels; noise abatement in the propagating media – the source and receiver separation using special structures, such as noise barriers; noise reception area improvements – mainly building insulation.

In the 6.1. fig. is shown the schematic diagram of the rolling noise model – the main noise source on Latvian railway and the main potential means of reducing rolling noise [16].



6.1. fig. Rolling noise model and main potential means of reducing rolling noise

The acoustic effects of various railway noise reduction measures are summarized in 6.1. table. Where available the estimated average for European market costs are also listed. [22]

6.5.1. table

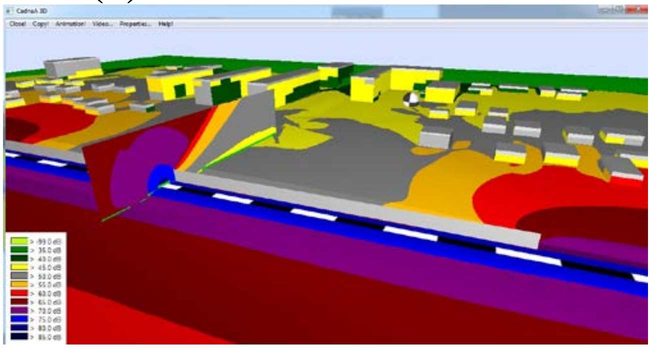
Acoustic effects of railway noise reduction measures and costs

Measure	Reduced noise source	Effect	Costs
K – blocks	Rolling noise	Up to 10 dB(A)	4000-1000 Euros per wagon
LL - blocks	Rolling noise	Up to 10 dB(A)	500-2000 Euros per wagon
General grinding of corrugated track	Rolling noise	Up to 20 dB(A)	Shall be established in normal maintenance
Acoustic grinding	Rolling noise	1-4 dB(A) depending on local rail and wheel roughness	
Disk brakes	Rolling noise	Up to 10 dB(A)	Mostly established in passenger cars
Wheel dampers and absorbers	Wheel noise	2-7 dB(A)	3000-8000 Euros per wheel
Trackside barriers with train side skirts	Wheel noise	8-10 dB(A)	
Rail dampers	Rail noise	3-7 dB(A)	300-400 Euros per meter
Rail pads	Rail noise	3-4 dB(A)	
Squeal noise measures	Squeal noise	Up to 20 dB(A)	
Shielding of pantographs	Aerodynamic noise	5-10 dB(A)	
Barriers 2 m high	All sources	10 dB(A)	1000 Euros per meter
Barriers 3-4 m high	All sources	15 dB(A)	1350-1700 Euros per meter
Insulated windows	All sources	10-30 dB(A)	

There are many noise source reduction and noise abatement measures available on the market. Although the price is high, noise barriers remain the most popular and universal approach to local railway noise mitigation. Let us consider some noise barrier planning examples performed by author for the area of Plavinas gymnasium discussed in chapter 5.

After the correct noise map was obtained, 5.4. fig. and the excess of limit noise levels by 2 dB(A) at the most exposed gymnasium facade was identified, it was required to propose a preventative noise reduction measure during the planned railway line reconstruction. The acoustical effect of few barriers of different heights and lengths placed parallel to the track at the distance of 3 m from the track was modeled. It was found that 200 meters long noise barrier with the height of 2 m, 3 m and 4 m reduces the noise levels at gymnasium facade by 5 dB(A), 6 dB(A) and 7 dB(A) correspondingly. The example of 4 m high barrier effect is shown in 6.2. fig.

Different colors on the noise map correspond to different noise levels with the step of 5 dB(A). The blue color corresponds to levels above 75 dB(A); violet – above 70 dB(A); dark red – above 65 dB(A); red – above 60 dB(A); dark yellow – above 55 dB(A); grey – above 50 dB(A) and yellow - above 45 dB(A).



6.2. fig. CadnaA modeled noise reduction by 4 m high and 200 m long noise barrier

The reduction of 5 dB(A) is more than enough for that particular case and 2 m high barrier can be used. Low height barriers are much cheaper and introduce less negative visual impact. However, it is important to take into account that the barrier will be less effective in noise abatement from the second line which will be placed further from the barrier. Although, considering the effectiveness of track source reduction measures in 6.1. table, the better cost/effectiveness ratio would be probably achieved using 2 m high noise barrier and rail tuned dampers.

For large scale projects, such as noise reduction on the whole railway network the best cost/effectiveness is achieved by the source reduction. The EU recommended measure number one for rolling noise reduction is the retrofitting of tread-braked freight and passenger rolling stocks with new type composite brake blocks. Composite brake blocks provide better braking performance, reduced braking noise levels and the most important keep the wheel rolling surface smooth. Currently the funding possibilities for braking system retrofitting on European railways are actively discussed in EU. The particular problem of Latvian railway is that about 60 % of railway traffic is freight traffic and main part of freight trains comes from neighboring countries Russia and Belarus, which are not EU member states, therefore the retrofitting of freight trains operating on Latvian railway is a very complicated political question. However, it is possible to follow good practice of European rail operators and use the increased excess charges for noisy trains coming from abroad. The braking system retrofitting would be an effective measure for rolling and braking noise reduction of Electric trains on Latvian railway.

The track component source reduction together with the noise barriers is a promising solution for train pass by noise reduction on Latvian railway. The acoustical effect of rail reprofiling by grinding should be monitored and existing rail joints eliminated or changed to acoustically improved joints. The effect from tuned rail pads and dampers should be investigated.

7. PROSPECTS FOR ENHANCEMENT OF LEGISLATIVE AND STANDARD BASE IN THE FIELD OF ACOUSTIC ECOLOGY

At the end of 2011, just after the TSI 2011 [28] were approved, the European Federation for Transport and Environment taking into account WHO recommendations and various devoted to railway noise reduction project achievements (chapter 6), proposed recommendations on TSI 2011 revision [21].

The following key aspects are to be covered: tightening of noise limits; inclusion of infrastructure into the noise regulations; inclusion of maintenance requirements for the vehicles; assessment of the TSI noise costs and benefits; use of continuous limit curve for freight wagons (currently a step function); inclusion of additional noise types/sources such as brake and curve squeal.

All these aspects are important for railway noise reduction, but there are pros and cons for Ministry of Transport of the Republic of Latvia. From one side the approved tightened railway noise limits will probably introduce possibilities to request the EU funding support for railway infrastructure modernization which is always good. But from other side if the EU funding is not available, Ministry of Transport will have to look for internal finances for TSI implementation. Taking into account current condition of Latvian railway infrastructure this does not seem to be possible. Thus, in order to avoid legislative problems in future, probably the most reasonable solution for Latvian railway is introduction of a special case in TSI for Latvia (and other Baltic states) based on experimentally obtained information about current acoustical situation. The results of current work can also be used.

Author proposes that based on current work results Latvian railway together with Ministry of Transport should initiate project on official improvement of EU interim method for railway noise modeling with respect to Latvian railway conditions.

One of the possible ways of getting funds for research and development is the use of European rail operator experience in definition of access charges based on rolling stock noise radiation levels, however this is a complicated political question.

Some other important aspects are linked with the currently approved regulations of Latvian cabinet of ministers Nr. 597 [23]. It is stated in [23] that the noise level limits listed in 5.1. table should be considered as goal levels for area parts situated closer than 30 m from the constant source. Author proposes that this statement should apply also for railway, considering the railway together with the railway alienation zone as the source.

Author assumes, that it is not correct to use only the 4 m height for strategic noise map preparation. People walking in the area of interest can be considered as receiver points at about 1.5 – 2 m height above the ground. Moreover, the difference in noise levels between the heights of 1.5 - 2 m and 4 m may be considerably affected by the presence of fence surrounding the area. This situation also applies for one floor detached houses where receivers (people) are also at the height of 1.5 – 2 m. Therefore author recommends that for the open areas and residential areas with one floor detached houses the noise levels should be evaluated at the height of 1.5 – 2 m.

Another important problems related to railway noise not considered in this work are internal train noise and exposure of railway employees to noise. Considering results of train pass by noise investigations it might be expected that train passengers suffer from increased noise levels during travelling. Many of railway employees are working on the trains or near the railway lines and are exposed to high noise levels most part of the working shift.

Moreover, all current standards consider the A-weighted noise levels. Author shares opinion of many scientists that this is a wrong approach. It was scientifically proved that sound affects human organism even when it is out of audible range. If the A-weighting function is not applied to the measured train pass by noise spectrum, noise levels at low frequencies may be similar or even higher than in audible range [18].

Every human organism from the acoustical point of view is a specific oscillating system, with separate elements (organs) making complex oscillations in wide frequency range from infrasound to ultrasound and under external influence of sound and vibration waves the resonant effects in different parts of human organism can occur. Such resonances can cause both, positive or negative effects on human health and wellbeing. [19]

Thus, it is very important to pay attention to the ultrasound which often is not audible, but propagates on long distances with very low attenuation and may disturb inhabitants especially during night time.

One more important problem is the “annoyance” of passing trains, which is currently not regulated. Results of some investigations show that the number of “annoyance” events during human sleeping time have probably bigger negative effect than the exposure to increased equivalent noise level. Imagine a long freight train passing only once a night, then the sleeping person is likely to be awaken only once due to increased noise level. If the train is divided into 3 parts the equivalent noise level for the night period of time will remain the same, but the person is likely to be awaken three times.

CONCLUSIONS

This promotion thesis is devoted to modeling and experimental investigations of railway transport noise spectra.

1. Analysis of railway noise sources had shown that the main noise source types at the speeds up to 250 km/h are traction noise and rolling noise. Rolling noise levels strongly depend on wheel and rail rolling surface roughness, what was proved by measurement results.

Taking into account results of analysis of modern railway noise modeling methods and European Commission recommendations, RMR, the Netherland modeling method was chosen for detailed evaluation in the thesis.

2. Results of experimental investigations of Latvian train pass by noise spectra had shown:

- Relatively high noise levels in all octave bands for all train types. The common peak for all train types is found in the 1 kHz octave band. In the case of freight trains the second peak is found in the 2 kHz octave band. These peaks are probably related to rail noise radiation.
- Diesel passenger trains radiate low frequency traction noise with considerably higher levels at speeds close to maximal. At lower speeds traction noise is dominant for locomotives in the octave bands up to 500 Hz. The considerable traction noise level in 63 Hz octave band is found for the case of freight locomotives.
- The total equivalent A-weighted pass by noise levels of all train types on Latvian railway don’t meet the TSI requirements. This fact should be taken into account by Latvian railway in order to prepare recommendations on special case introduction for Latvian railway in the revised version of TSI coming in 2013.
- Because of the smoother wheel rolling surface, rolling noise levels of disc-braked diesel passenger trains on a relatively smooth track are about 5 dB(A) below the noise levels of tread-braked electric trains. Most noisy found to be the freight trains.
- In case of freight rolling stock used on Latvian railway, it is essential to divide freight trains into subcategories in terms of noise radiation. The freight rolling stock consisting only from wagons found to have considerably lower pass by noise levels compared to other types of freight rolling stock. If it is required to reduce the noise radiation from a railway line, the reduction of freight train radiation is of the most importance.
- The pass by noise level with increasing the speed by 40 km/h increases by approximately by 5.5 dB(A) in case of electric trains; 7 dB(A) in case of diesel passenger trains and 2.5 dB(A) only in case of mixed freight trains. From this follows that the decrease of train speed as a rolling noise reduction measure is less effective for freight trains.
- The total pas by noise level due to impact noise from 15-20 mm wide rail joint can be increased by about 10-12 dB(A). The noise levels are increased in all octave bands, therefore in places where rail joints remain it is likely that the impact noise will be the dominant noise source.
- The braking squeal noise in case of Latvian electric trains occurs at frequencies higher than in European train case. The total noise level can be increased by about 10 dB(A) due to braking squeal noise. The squeal being highly tonal is very annoying both for passengers outside and inside the train. However, it is possible to stop the train without any considerable increase in noise levels if the low braking force is applied in a due time.

- Poor quality rail reprofiling by grinding may result in significantly increased pass by noise levels of all train types in all octave bands and at all speeds. Investigation results were used by Latvian railway to claim the free of charge rail regrinding. The rail grinding quality can be improved increasing the number of grinding machine passages and decreasing the grinding speed at least for the last passage.

3. The comparable analysis of measurement and modeling results had shown that the measured pass by noise spectrums of Latvian trains in average track conditions have significantly higher levels in all octave bands than those modeled using EU recommended method. The difference between total levels is about 10 dB(A) in case of electric and diesel passenger trains and up to 20 dB(A) in case of freight trains. Thus, proving that the EU recommended method for railway noise modeling should be improved before application in Latvian railway conditions.

4. The algorithm of train pass by noise spectrum calculation in the reference point of reception was developed and software implemented (TNS). Using TNS five new types of Latvian trains were defined based on results of experimental investigations for modeling with RMR method in average for Latvian railway track conditions. The level of noise mapping result accuracy is considerably improved by using TNS and defined train categories.

Author proposes that based on current work results Latvian railway together with Ministry of Transport should initiate project on official RMR method improvement for Latvian railway conditions.

5. The analysis of noise source reduction and noise abatement possibilities on Latvian railway had shown that the particular problem of Latvian railway is that about 60 % of railway traffic is freight traffic and main part of freight trains comes from neighboring countries Russia and Belarus, which are not EU member states, therefore the retrofitting of freight trains operating on Latvian railway is a very complicated political question. However, it is possible to follow good practice of European rail operators and use the increased excess charges for noisy trains coming from abroad. The braking system retrofitting would be an effective measure for rolling and braking noise reduction of Electric trains on Latvian railway.

The track component source reduction together with the noise barriers is a promising solution for train pass by noise reduction on Latvian railway. The acoustical effect of rail reprofiling by grinding should be monitored and existing rail joints eliminated or changed to acoustically improved joints. The effect from tuned rail pads and dampers should be investigated.

Future work

The future investigations will involve more extensive research of traction, impact and curve squeal noise and source separation. It is planned to develop the automated multi-channel monitoring station with respect to specific railway noise measurement requirements.

Currently is being implemented financed by Latvian railway project for evaluation of official action plan for noise reduction and preparation of improved action plan in 2012.

Was approved and currently being launched prepared in 2011 by Latvian railway together with RTU (Institute of railway transport) and privately held Latvian company Composite Constructions project LIFE11 ENV/LV/376 ISRNM Innovative Solutions for Railway Noise Management under the European “LIFE+” funding scheme. The project will be continuation of current research and is devoted to in deep investigation of railway noise on Latvian railway, improvement of EU recommended method for railway noise modeling in Latvian railway conditions and development of new type of noise barriers and track component noise reduction. The project will have not only scientific and practical, but also economical effect, because all noise source reduction and noise abatement tools will be produced in Latvia and will be later available both for internal market and export.

REFERENCES

1. Baranovskii A. Adaptation of RMR noise propagation prediction method for Latvian railway conditions // Proceedings of the 7th International Scientific Conference TRANSBALTICA 2011, Lithuania, Vilnius, May 05-06, 2011. – 11-15 pp.
2. Baranovskii A. Application of RMR method for noise prediction on Latvian railway // Proceedings of the International Scientific Conference Signal and Image Processing and Applications (SIPA 2011), Greece, Hersonissos, June 22-24, 2011. - 33–38 pp.
3. Baranovskii A. Comparison of five national noise emission calculation methods for rail traffic // Proceedings of the 5th International Scientific Conference Intelligent Technologies in Logistics and Mechatronics Systems (ITELMS'2010), Lithuania, Panevezys, May 03-04, 2012. – 7-12 pp.
4. Baranovskii A. Computer simulation and experimental investigations of noise levels and spectra for railway transport // Automatic control and computer sciences. – 2011. - Vol. 45, Nr. 5. – 293-300 pp.
5. Baranovskii A. Experimental investigation of railway noise and railway noise mapping in Latvia // Proceedings of the 19th International Congress on Sound and Vibration (ICSV'19), Lithuania, Vilnius, July 08-12, 2012. – 8 pp. (CD-ROM)
6. Baranovskii A. Railway noise abatement at Plavinas gymnasium // Scientific proceedings of RTU. Transport and engineering. Railway transport. – 2012. – Series 6, Vol. 34. – 3 pp. (accepted for publishing)
7. Baranovskii A. Railway noise in Latvia // Proceedings of the 7th International Scientific Conference Intelligent Technologies in Logistics and Mechatronics Systems (ITELMS'2012), Lithuania, Panevezys, May 03-04, 2012. – 5 pp. (accepted for publishing)
8. Baranovskis A. Dzelzceļa ritošā sastāva trokšņa mērījumu rezultātu apstrādes un kartēšanas metodikas izstrāde un dzelzceļa darbinieku apmācība, projekta atskaite, LDz, Rīga, 2012.
9. Beek A., Beuving M., Dittrich M. and others. Rail sources, state of the art. Report on the task 1.2.1 of the Harmonoise Project, SNCF, France, 2002.
10. LDz, RTU IRT, Composite constructions. Innovative Solutions for Railway Noise Management, general description of LIFE11 ENV/LV/376 ISRNM research project under Life+ 2011 program for Environment policy and governance, Riga, 2011.
11. Meehan P. A. Railway noise and control. The workbook for the course in engineering acoustics. – Queensland: The University of Queensland, 2006.
12. Noordhoek I.M., Salomons E.M. Choise of basic sound propagation models. Deliverable 14 of the Harmonoise project, TNO, Netherlands, 2002.
13. Nota R., Barelds R., Van Maercke D. Harmonoise WP 3 engineering method for road traffic and railway noise after validation and fine-tuning, DGMR, The Netherlands, 2005.
14. P. de Vos, M. Beuving, E. Verheijen. Harmonised accurate and reliable methods for the EU directive in the assessment and management of environmental noise. Deliverable 4 of the Harmonoise project, AEA Technology, Netherlands, 2005.
15. Salomons E.M., Heimann D. Description of the reference model. Deliverable 16 of the Harmonoise project, TNO, Netherlands, 2004.
16. Thompson D. Railway Noise and Vibration. – Oxford: Elsevier, 2009. – 518 pp.
17. Попов В., Балцкарс П., Барановский А., Ильина Л. Экспериментальные исследования уровней шума железнодорожного подвижного состава // RTU zinātniskie raksti. Mašīnzinātne un transports. Dzelzceļa transports. – 2008. – Sējums 6, Sērija 30. – 29-37 lpp.

18. Попов В., Балцкарс П., Барановский А. Математическая модель CRN шума железнодорожного подвижного состава // RTU zinātniskie raksti. Mašīnzinātne un transports. Dzelzceļa transports. – 2008. – Sējums 6, Sērija 30. – 21-29 lpp.
19. Попов В.И. Основы музыкальной акустики.- Рига: Издательство Рижского технического университета, 2010. - 427 с.
20. LVS EN ISO 3095:2005. Dzelzceļa aprīkojums. Akustika. Dzelzceļa ritošā sastāva radītā trokšņa mērīšana, Latvijas Valsts Standarts, 2005.
21. European Federation for Transport and Environment: Revision of EU rail noise standards (TSI 2011) / Internet. – www.transportenvironment.org
22. European parliament: Reducing railway noise / Internet.- http://www.europarl.europa.eu/studies
23. Latvijas Ministru kabinets: MK noteikumi Nr. 597. Trokšņa novērtēšanas un pārvaldības kārtība / Internet.- www.likumi.lv
24. Nederland Ministerie van Volkshuisvesting: Reken - en Meetvoorschrift Railverkeerslawaai (1996) / Internet.- stillerverkeer.nl
25. Noise steering group: Adaptation and revision of the interim noise computation method for the purpose of strategic noise mapping / Internet.- circa.europa.eu
26. Noise steering group: Administrative arrangement between DG ENV and DG JRC on "Technical advice on the preparation of the common European assessment methods to be used by the EU Member States for strategic noise mapping after adoption as specified in the Directive 2002/49/EC" / Internet.- circa.europa.eu
27. Official journal of the European Union: Commission decision 2002/735/EC concerning the Technical specifications for interoperability (TSI) relating to the rolling stock subsystem of the trans-European high-speed rail system / Internet. – eur-lex.europa.eu
28. Official journal of the European Union: Commission decision 2011/229/EU concerning the Technical specifications for interoperability (TSI) relating to the rolling stock subsystem of the trans-European conventional rail system / Internet. – eur-lex.europa.eu
29. Official journal of the European Union: Position paper on the European strategies and priorities for railway noise abatement / Internet. – eur-lex.europa.eu