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Problems of Railway Noise—A Case Study

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Under Directive 2002/49/EC relating to the assessment and management of environmental noise, all European countries are obliged to model their environmental noise levels in heavily populated areas. Some countries have their own national method, to predict noise but most have not created one yet. The recommendation for countries that do not have their own model is to use an interim method. The Dutch SRM II scheme is suggested for railways. In addition to the Dutch model, this paper describes and discusses 3 other national methods. Moreover, discrepancies between the HARMONOISE and IMAGINE projects are analysed. The results of rail traffic noise measurements are compared with national methods.

rail traffic noise   national government legislation and regulations
European Community requirements   noise-generating devices   rolling contact noise sources
rail vehicle noise

1. INTRODUCTION

Rail is perceived as one of the most environmentally friendly means of transport [1]. However, noise pollution from railways is significant. One-third of the Polish population is exposed to a noise level exceeding legal regulations [2]. Passenger trains in Poland are mostly electric, but the noise level for freight trains is high. Emission of CO_2 should also be considered. However, a comparison of road and rail noise shows that rail noise still has a lower impact on the environment. That is why many European research studies focus on this area. This may help to restore interest in railways as a means of transport which is really necessary in Poland. These facts have become a motivation to modernize the main railways and to promote high-speed trains in Poland.

The paper is organized as follows. First, there is a short review of European Union (EU) directives and studies related to noise control. Section 2 describes the French, German, Nordic and Dutch calculation models. Then the outlines of HARMONOISE [3] and IMAGINE [4] projects are described. A multimedia computer system for monitoring environmental threats engineered at the Gdańsk University of Technology is briefly introduced with the main focus on implementing the railway noise prediction model in HAROMONOISE and IMAGINE. Moreover, noise measurements and predictions based on those methods are compared and conclusions are drawn.

1.1. EU Directives

The European Commission (EC) considers environmental noise and related problems very important, so European Directive 2002/49/EC followed. Homogenous treatment of noise problems in all EU countries, understanding methods of reduction, prevention and avoidance of the adverse effects

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of noise have become of key interest [5]. The directive obligates member states to provide access to information on noise pollution. The public in each country should be aware of the problem and its scale (cf. Ustawa… [6]). According to the requirements of the directive all "member states should ensure that no later than 30th June 2007 strategic noise maps showing the situation in the preceding calendar year have been made and, where relevant, approved by the competent authorities, for all agglomerations with more than 250000 inhabitants and for all major roads which have more than six million vehicle passages a year, major railways which have more than 60000 train passages per year" (p. 15) [5]. Then, by mid-2012 measurements should be adopted for all agglomerations, main roads and main railways to create strategic maps every 5 years. That is why, Annex II of Directive 2002/49/EC determines common computation methods of these strategic noise maps. These are four interim computation methods [7]. They are described in greater detail in section 2. Within the last few years, the EC produced several important documents, mostly good practice guides on strategic noise mapping [1].

1.2. Related Studies

Many Polish institutions and scientists are interested in noise prediction [8]. Recently, Gołębiewski and Makarewicz thoroughly compared two methods of railway noise propagation [9]. They first reviewed the recommendations of the EU directive in the context of road traffic, tram, aircraft, industrial and railway noise, and then compared two methods of railway noise propagation: one recommended by the EU, the other developed at the Adam Mickiewicz University in Poznań, Poland. The results showed that those two methods provided similar outcomes, which is encouraging. Earlier, Gołębiewski and Makarewicz identified the problem of downward refraction and turbulence that affect railroad noise [10].

Thompson, a very good source on railway noise and vibration, thoroughly explained rolling noise, curve squeal, bridge noise, aerodynamic noise, ground vibration, ground-borne noise, vehicle interior noise, etc. [11]. Janssens, Dittrich, de Beer, et al. discussed estimating effective roughness from rail vibration measurements under traffic; they used spectral characteristics of vibration during a train pass-by and three correction factors [12].

Currently many studies are undertaken to quantify the uncertainties involved in noise mapping to minimize errors in practical applications. Nilsson, Jones, Thompson, et al. showed that although engineering methods for modelling the generation of railway rolling noise were well established, they involved some simplifying assumptions to calculate the sound powers radiated by the wheel and the track [13]. Earlier studies also indicated the problem of uncertainties in both measurements and noise prediction [14, 15, 16]. Batko and Stępień also outlined the problem of calculating noise level; they assessed estimates of uncertainty of noise indices L_{den} and L_{n} for day and night, respectively [17]. They suggested non-parametric estimators of a probability density function in calculating type A standard uncertainty of environmental noise hazard indices. The study was based on continuous monitoring of traffic noise recorded on a main artery in Kraków, Poland, in 2004 and 2005.

Calixto, Pulsides and Zannin presented an interesting aspect of noise modelling [18]. They studied noise emission levels in a urban area: they measured noise levels, vehicle flow and traffic composition. Vehicle flow and traffic composition were used to estimate sound emission levels with mathematical models. They proved that the results of prediction models agreed well with the measured noise levels. Probst indicated that if there was a three-dimensional model of an environment, it would be easier to communicate an existing noise problem to decision makers and to improve the situation [19].

Kucharski proposed a complex noise indicator for noise mapping; it was based on EU working groups and results of Polish studies of annoyance [20]. Those studies were carried out as part of the annual Noise Monitoring System project (co-ordinated by the Chief Inspectorate of Environmental Protection). Czyżewski, Kostek and Kotus presented a complex study on measuring and predicting noise including building environmental noise technology [21]. This study used noise measurements and a parallel-processing supercomputer to update noise maps in the area of Gdańsk. Szczodrak, Czyżewski and Kotus investigated road noise with an automatic noise monitoring station developed at the Gdańsk University of Technology [22]. Kotus and Kostek described a system monitoring dynamic noise for examining the impact of noise on hearing; it is based on the concept of psychoacoustic noise dosimetry [23]. Dąbrowski, Dziurdź and Klekot studied propagation of vibroacoustic energy and its influence on structure vibration in a large building [24]. This was important in the context of acoustically induced vibrations of construction elements, such as rail structures.

Some studies explicitly consider the problem of human exposure to noise. For example, Kompała and Lipowczan studied noise hazard affecting the population of areas living and working at road border crossings [25], as did Preis and Gołębiewski [26]. Kotus and Kostek [23] and Czyżewski, Kotus and Kostek [27] studied assessment of noise-induced harmful effects based on the properties of the human hearing system. Their noise dosimeter makes it possible to assess affecting temporary threshold shift in critical bands in real time.

2. EUROPEAN NOISE PREDICTION MODELS

2.1. Interim Methods

Under a recomendation of the Commission of the European Communities, strategic noise maps should be based on national methods if the country has one [7]. If not, four interim calculation methods were proposed. There are no national prediction models for Poland. Therefore, for railway noise, the 1996 RMR Netherlands national computation method was recommended [7].

The differences between the best European prediction methods are very interesting. The same issue was raised during HARMONOISE [3]. Researchers in this project compared European national prediction methods. The best four methods laid the foundations for a new European prediction model, which should be used in all member states. They are German Schall 03 [3], Dutch SRM II [28], the Nordic model [29] and French NMPB-FER [3].

2.2. Schall 03

The German Schall 03 model has very clear rules and is easy to use [3]. It is based on a fixed value of 51 dB for all noise events. Then corrections for different acoustical actions related to train pass-bys are added. Ten corrections have been categorized; in a way they are uncertainty elements since in some cases not all them can be identified. The first group is associated with train properties. These are train type, train speed and brake types. Next, there are some corrections related to track properties and track support structures. The last group concerns the mechanism of sound propagation and parameters such as the sound pressure level and the angle between the direction of the train and sound propagation. Parameters that are related to bridges, level-crossings and curves have also been defined. Equation 1 presents the general rule of predicting noise:

$$L_{pE} = 51 + C_{cat} + C_{intensity} + C_{speed} + C_{angle} + C_{track} + C_{bridge} + C_{DI} + C_{brake} + C_{crossing} + C_{radius}, \quad (1)$$

where L_{pE}— A-weighted sound pressure level per length of vehicle in decibels, C_{cat}—correction for category, C_{DI}—correction for directivity, C_x—correction for x.

Noise level is calculated using source segmentation. For each element, noise level is computed and then those values are added. The problem is that neither the frequency dependence on railway noise nor atmospheric conditions are considered. Even if source directivity is included in the prediction model, physical mechanisms that involve sound propagation are not considered [3]. That is the only method described in this paper, which does not consider noise frequency dependencies. First and foremost, that model has a very clear construction and it is easy to implement, because it takes into account only a few important parameters. However, the method is too limited to become a European prediction model for noise mapping. Its updated version appeared in 2006, but it did not resolve all problems [30].

2.3. SRM II

The Dutch SRM II model precisely describes the relation between noise level and noise source [28]. The modelling is performed in octave bands. That is the fundamental difference between the method discussed in section 2.2 and this one. Modelling is done in bands from 63 to 8000 Hz. Another change is that heights of sources are considered, which makes predicting the effect of noise barriers possible. Like in the German model, the number of trains daily during day and night, train category and the track structure are the main parameters; they include sleeper type, the number of rail segments, joints and crossings and the ratio of brake time to the entire time of the train ride. Equation 2 is used to calculated emission of noise [3]:

$$E_c = a_c + b_c \cdot \log v_c + 10 \log Q_c + K_{\text{tr}}, \quad (2)$$

where c—train category index, a_c—emission for a particular octave band depending on frequency and category, b_c—fixed value dependent on the octave band, source height and train category used for adjusting train velocity, K_{tr}—fixed value dependent on the rail type, v_c—train velocity for c category in kilometers per hour, Q_c—number of pass-bys for c category per hour.

Equation 2 shows that the height of the source and some prefixed values for certain frequency band are defined. The easy-to-use classification of trains on the basis of the type of train and braking system is an important advantage; it makes the Dutch method easy to customize for any European country. The ASWIN database[1] helps in using SRM II [3]. It contains information about types of tracks and parameters related to train traffic, e.g., the average speed of passing-by trains and the average number of pass-bys per hour and train category. Such a database is extremely important, especially in view of the requirements of Directive 2002/49/EC [5]. Poland does not have its own prediction method, so SRM II should be adapted to noise mapping. This method does not consider detailed technical parameters of individual trains. However, it is crucial to know the type of brakes, drive and train, e.g., whether it is a passenger or freight train. It should be noted that this method was developed for standard Dutch tracks.

2.4. NMPB-FER

The French model promotes the existing road prediction method in that country. The NMPB-FER has a highly developed propagation part, which assumes two cases, favourable and atmospheric homogeneous conditions for sound propagation [3]. Calculations of noise levels for both cases are followed by combining them using a percentage time of occurrence. The modelling result is a long-term, equivalent *A*-weighted noise level. Two different sources heights are considered. The lowest frequencies, i.e., 125, 250 and 500 Hz, are considered at 80 cm and the highest ones, i.e., 1, 2, 4 kHz, at 5 cm above the rolling plane. Train categorization is quite simple, but track conditions are not specified. The main advantage of this model is that it is well defined in three-dimensional directivity, which is assigned to the sources. This model defines directivity on the horizontal plane that corresponds to the sound emission resulting from the rolling elements and the infrastructure. On the other hand, directivity on the vertical plane is linked to the body of the carriage concealing the sources [3]. The propagation part of the French model is the most advanced one within the methods introduced in this paper. That is why the NMPB-FER has been recognized as important.

2.5. Nordic

The Nordic countries have long-lasting traditions in modelling noise prediction. They have engineered a common method that takes two

[1] Aswin—a rail source database of The Netherlands. AEA Technology Rail BV; 2004.

source cases into consideration. First, total traffic for all combinations of parameters, i.e., trains and operating conditions. It is used to calculate the equivalent noise level. The second model is designed for individual trains and operating conditions, which makes it possible to determine the maximum noise level for a given train situation. The propagation part, as in the Dutch model [28], allows modelling a positive range of temperatures, and using this scheme downwind. This model, called NMT 96 [29], was developed, and Nord 2000 came into existence. However, HARMONOISE did not consider it because it was not yet completed at that time. Nord 2000 generates calculations from 25 to 10 000 Hz in one-third-octave bands. Moreover, very detailed atmospheric conditions are taken into account [3]. Probably, if Nord 2000 were compared with other European prediction methods at the beginning of HARMONOISE, it would have received the highest mark and would have become the starting point for HARMONOISE and IMAGINE [4].

3. HARMONOISE AND IMAGINE PROJECTS

The main goal of Directive 2002/49/EC has been to provide a homogenous approach to noise problems in the EU [5]. The list of problems includes understanding the methods of reducing, preventing and avoiding adverse effects of the noise, etc. The Directive says that environmental protection is possible by "complementing the action of the Member States by a Community action achieving a common understanding of the noise problem. Data about environmental noise levels should therefore be collected, collated or reported in accordance with comparable criteria. This implies the use of harmonized indicators and evaluation methods, as well as criteria for the alignment of noise-mapping" (p. 12) [5]. This obliged researchers to address the problem. HARMONOISE [3] and then IMAGINE [4] attempted to deliver a model which improved prediction results in all EU countries. The main problem with using national models in each country is that they cannot be compared because of different definitions of noise factors. For example, defining velocity is a problem. The dependence of the train speed logarithm on predicted noise is given in the form of a coefficient, which can be a fixed value, 20 or 30, or as in the Nordic [29] and Dutch [28] models, a frequency-dependent value. In addition, in those models speed is divided by 100 or by a reference value provided by that model. It is not possible to choose the best estimate, because it contains parameters specific for a country, which unfortunately is not explicit. This is a root cause of problems with determining the correct dependence of noise level on train velocity. These kinds of problems can be seen clearly in the propagation parts of the models [31, 32, 33].

To compare prediction results feasible in the EU, common indicators for all European countries had to be determined. That is why, different calculation schemes returned incompatible results for the same modelled situation. So, two basic indicators were identified: L_{den} for evaluating day noise annoyance and L_{night} (or L_{n}) to indicate sleep disturbance [5].

The next objective of IMAGINE was to create a database with a universal structure, because several countries had problems with categorizing trains [4]. Train descriptor definitions were prepared within the framework of the EU-funded STAIRRS[2] project (Strategies and Tools to Assess and Implement noise Reducing measures for Railway Systems). These descriptors can be used in translating national categories into a common European classification. This database includes seven parameters related to trains: train type, number of axles, length of the train, coach type, load, wheel diameter and brake type [4]. The corresponding descriptor is a single alphanumerical symbol.

HARMONOISE and IMAGINE distinguish three types of railway noise or, more precisely, three types of railway noise sources: rolling,

[2] http://www.stairrs.org

traction and aerodynamic. Rolling noise is caused by the interaction between the wheel and the track. The friction pair is of main interest in this case. The type of engine and train, and the ventilation system are the main sources of traction noise. The last of the three noise sources, i.e., aerodynamic noise, includes air motion and pantograph influence. Figure 1 presents noise source domination in the total noise level, depending on train speed [3]. Rolling noise is measured in this model at 0 and 0.5 m above the rail head, traction noise is calculated at 0.5, 2, 3, 4 m and aerodynamic noise can be best measured at 0.5 and 4 m.

This new model considers such parameters as impact noise (part of rolling noise), curve and brake squeal and braking. All of them are calculated at 0.5 m above the rail surface. The important differences in comparison with national methods are the distance of 7.5 m from the track centerline and measurements and calculations done at 1.2 m.

4. MULTIMEDIA COMPUTER SYSTEM FOR MONITORING ENVIRONMENTAL NOISE

Czyżewski, Kostek and Kotus developed a multimedia computer system for monitoring environmental noise (MSMN) [21]. Its functionalities related to controlling environmental noise used measurements made in the city. The main part of MSMN is a central database with measurements and tools necessary to measure noise levels. This project proposes a mobile noise monitoring station with software that calculates environmental noise prediction based on experience from HARMONOISE [3] and IMAGINE [4]. Moreover, wireless data transmission technology is used to send data to the server and to control the work of the stations [21]. The modelling of the acoustic field is computationally complex [34], thus all methods are implemented on a parallel-processing supercomputer [35]. The results of modelling are presented as a noise map [36]. The implementation of the railway noise prediction model is part of the MNMS software; it is now integrated with road prediction and propagation—all three based on the HARMONOISE and IMAGINE requirements and functionalities.

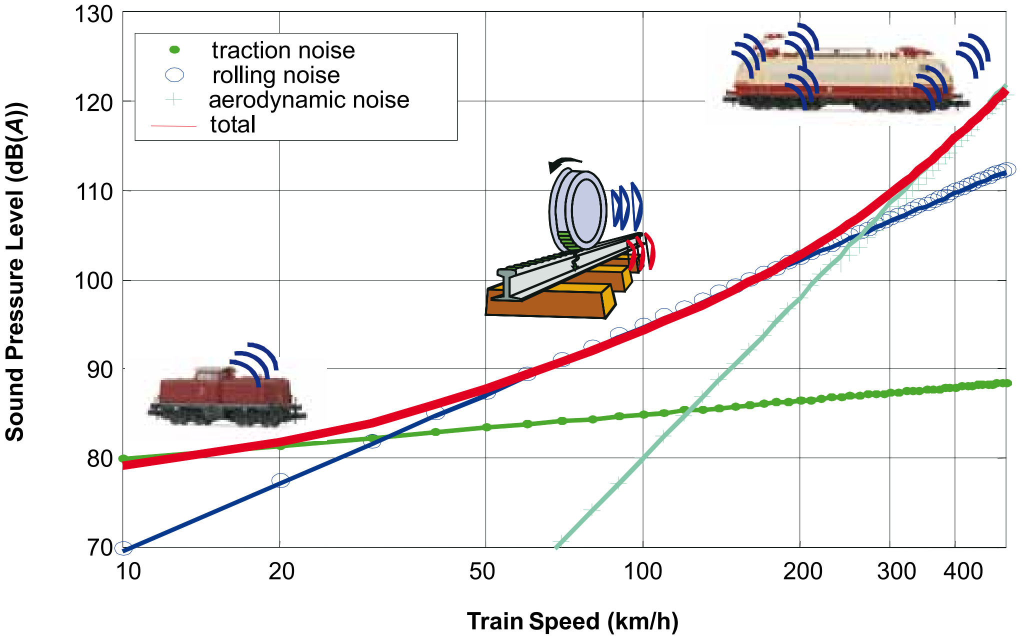

Figure 1. Relative strength and speed dependence of sources of railway noise [3].

4.1. HARMONOISE Implementation of Railway Noise Prediction Model

The railway noise prediction model was implemented with C++ (GNU GCC 4.4.3, Free Software Foundation). It considers rolling, traction and aerodynamic noise, but for data reference it uses IMAGINE data only [4]. This limitation is necessary because there is no relevant database in Poland; however, we gathered parameters of Polish trains for this project.

The software has two parts. One describes the track segment, the other, the train. Propagation is computed in an external module of MSMN. The software uses reference data to compute noise level. To calculate the rolling noise, parameters of the track and trains are necessary. Then, from those functions, the interaction of both is computed. After those steps, the basis for rolling noise is ready. The next step in the process is adding rolling noise and traction and aerodynamic noise (functions taken from IMAGINE documentation [4]). Afterwards, frequency bands and *A*-weighting are added.

The first problem is that some functions are frequency-dependent, whereas other ones are wavelength-dependent. The result, i.e., the equivalent noise level, is also frequency-dependent, so there is the problem of adding third-octave bands. Wavelength is calculated at frequencies generated by the train depending on its velocity. Each train has a different speed, so for each train the shift between functions is different. As a result, functions should be carefully added. This problem is shown in Table 1. Function $L_{\mathrm{rimpact,nl}}$ is wavelength-dependent and vehicle transfer function is frequency-dependent. First, the simulation is made for 90 km/h, then for 72 km/h. In the first case, the shift equals one octave band, in the second one, a one-third-octave band.

This problem was resolved in the C++ implementation; however, it directly impacted the correctness of the results. Moreover, there were problems with compatibility of the IMAGINE data [4]. This issue is discussed in greater detail in section 6.3.

CadnaA 3.71 (DataKustik, Germany) is very useful for testing differences between national models, therefore, it was used in this study. It was important to compare the results of the IMAGINE model [4] implemented at the Gdańsk University of Technology with those of the national schemes [32]. This kind of comparison is limited because of the differences in definitions in each model, but in the situation that was measured, it was possible to see how suitable those models were for Polish conditions.

TABLE 1. Shift in Transfer Function in IMAGINE [4]

λ (cm)	$L_{\mathrm{rimpact,nl}}$	*f* (Hz) from λ (υ = 90 m/h)	*f* (Hz)	$L_{\mathrm{Hpr,nl,veh}}$
			20	27
			25	32
			32	37
63	22.4	39.7	40	42
50	23.8	50	50	47.4
40	24.7	62.5	63	51.9

λ (cm)	$L_{\mathrm{rimpact,nl}}$	*f* (Hz) from λ (υ = 72 km/h)	*f* (Hz)	$L_{\mathrm{Hpr,nl,veh}}$
			20	27
63	22.4	23.8	25	32
50	23.8	30	32	37
40	24.7	37.5	40	42
31.5	24.7	47.6	50	47.4

Notes. λ—wavelength (cm), *f*—frequency (Hz), υ—velocity of the train, $L_{\mathrm{rimpact,nl}}$—normalized impact roughness level, $L_{\mathrm{Hpr,nl,veh}}$—vehicle transfer function.

5. MEASUREMENTS

Relevant measurements had to be made to check the simulation result in Poland. Tests took place in Gdańsk, in spring. Table 2 shows train pass-bys and the results. For the HARMONOISE/ IMAGINE model [3, 4] each measurement corresponds to a single train passage. Temperature was 8 °C, relative humidity 80%.

Several parameters of each pass-by were recorded during the tests:

- train type and brake type, which were checked visually;
- time interval, which was determined with a stopwatch;
- train length based on the length unit database.

On this basis, the velocity of each train was estimated using the time interval and the length of the train. Velocity was calculated in metres per second, because of the HARMONOISE standard. The analyser was set up at the distance of ~7.5 m and the height of ~1.2 m in accordance with the assumption in IMAGINE.

National methods were tested for two continuous measurement series for regular trains for the same period of 40 min. During the first test 20 trains passed by, during the next one another nine. The *A*-weighted background noise in this place was 53 dB. The analyser was put 1.6 m above the ground and the distance from the track line was 20 m. Table 3 shows the measurements conditions.

6. MODELLING RESULTS FOR POLISH CONDITIONS

6.1. HARMONOISE

As mentioned before, the IMAGINE/HARMONOISE model was used as reference data for implementing noise prediction in C++. Comparing the real measured situation with

TABLE 2. Measurement Results

Train Type	Length (m)	Velocity (m/s)	*A*-Weighted Measured Noise Level (dB)
Electric, local	91	9.00	71.46
Electric, local	61	9.42	76.69
Passenger	61	10.20	79.90
Fast train	163	16.30	84.90
Electric, local	61	12.24	78.12
Electric, local	91	10.11	83.03
Passenger	91	15.16	80.60
Passenger	61	15.30	81.06
Electric, local	91	11.37	77.87

TABLE 3. Conditions for Both Measurements

Condition	Measurement 1	Measurement 2
Temperature (°C)	12	10
Relative air humidity (%)	80	91
Cloudiness	high	very high
Period (min)	40	40
Number of trains	20	9
A-weighted equivalent noise level (dB)	68.6	65.7
A-weighted maximum noise level (dB)	89	88.9
A-weighted minimum noise level (dB)	43.6	—

the values computed with the HARMONOISE model was a challenge. Table 4 contains three different railway equivalent noise levels. The first one is the measured value. The next one is related to the calculated rolling noise level, which in this case should have the biggest influence on the total noise level. The last column corresponds to the computed total equivalent *A*-weighted noise level including all parts defined in the HARMONOISE model, i.e., rolling, traction and aerodynamic noise. All values were obtained or simulated for the distance of 7.5 m from the railway.

For the nine train pass-bys, there were noticeable discrepancies between measurements and calculations. The total noise level was up to 20 dB (including all main parts of railway noise). The probable reason for the discrepancies was that calculations were performed ~7.5 m from the first track, whereas real measurement tests took place at various distances from the track centerline on which the train was passing. That was so because there were multiple parallel track lines. Some were used by passenger trains, others by electric ones. The analyser was placed ~7.5 m from the outer track line. That is why the difference between the real and the required distance was taken into account. In this case, the same correction resulting from a larger distance was included in the estimation procedure of the equivalent noise level L_{eq} prediction for these measurement tests. For more details, see Reiter and Kostek [32].

Firstly, the software calculated the noise level just for a single passage. Then noise for continuous measurements was estimated by adding the energy of the calculated noise levels for individual trains. In this case, the environmental noise level during the measurements was 53 dB. This basis allowed computing the noise level for the same time interval as the tests. In our case, it was 40 min. Table 5 shows the differences between the measurements and calculations for a given period.

TABLE 5. Comparison of Measurements and Computations of L_{eq} (dB)

No.	Computed $L_{eq}(r)$	Measurement Results (*A*-Weighted)
1	75.91	68.57
2	68.03	65.74

Notes. $L_{eq}(r)$—L_{eq} taking into account the distance *r* between the analyser and the track centerline.

$L_{eq}(r)$ denotes L_{eq}, in decibels, taking into account the distance *r* between the analyser and the track centerline. The difference in distance was compensated by complying to the general sound decay formula for open space. The most important indication from Table 5 is the dependence of the difference related to the number of trains. The greater the difference, the greater the number of trains (No. 1 in Table 5). The most probable explanation is that this discrepancy represents the accumulation of individual inaccuracies. Each observed and then computed pass-by has some inaccuracies

TABLE 4. Comparison of Computed and Measured Equivalent Noise Levels

Train Type	*A*-weighted Equivalent Noise Level (dB)		
	Measured	Computed Rolling	Computed Summary
Electric	71.5	82.8	92.05
Electric	76.7	84.6	93.79
Passenger	79.9	84.6	93.79
Fast train	84.9	83.9	87.19
Electric	78.1	85.2	93.88
Electric	83.0	83.5	92.05
Passenger	80.6	86.4	89.07
Passenger	81.1	88.9	91.44
Electric	77.9	83.5	92.05

in the measurement procedure and also in the parameters of reference data. Decreasing this difference is strongly recommended; this will be possible when all train pass-bys in Poland have their equivalent in HARMONOISE input data. Each European country has specific railway conditions and freight, so the problem consists in developing the concept of comparing railway noise in Europe. At the moment, the proposed reference parameters in the HARMONOISE model are correct for conditions in just a few countries, and the idea is to predict noise with similar discrepancies in all EU countries. This mainly refers to track and vehicle transfer functions and total effective roughness together with the built-in contact filter for individual friction pairs.

6.2. National noise prediction models

Each national method was modelled in the same place as the measurement tests in the HARMONOISE [3] continuous measurements. The predictions were performed in CadnaA 3.71 (DataKustik, Germany) software and based on its database. Like in the HARMONOISE model, the input data were prepared at the time of measurements. It was obligatory to classify all trains passing by the area, their brakes, velocity and length. These data were the basis for computing acoustic maps using German, Dutch and Nordic methodology [3, 28, 29]. Table 6 compares the two measurement sessions and computations for equivalent simulated atmospheric and traffic conditions. Moreover, the absolute inaccuracy of all three methods is indicated. A similar inaccuracy is presented in the German [3] and Nordic [29] schemes. It equals 0.4–1.5 dB; however, the discrepancy in the Dutch model [28] resulted in 4 dB for the first and over 6 dB for the second measurement. It should be stressed that each national prediction method is based on a unique set of railway rolling stock and traction conditions. This influence is difficult to estimate, because of the various definitions of trains and the parameters considered in each model.

Figures 2–4 show noise maps for the modelled area made with various prediction methods.

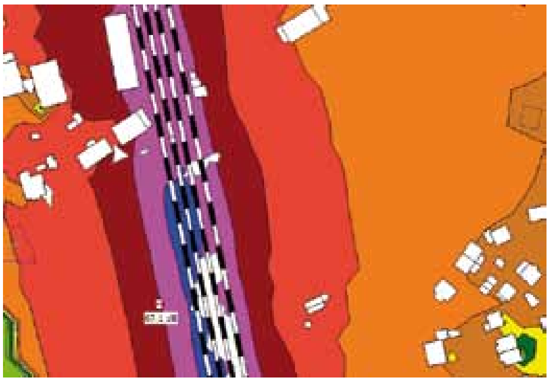

Figure 2. Map L_{day} calculated for a measurement point with Schall 03 [3]. *Notes.* L_{day}—*A*-weighted long-term average sound level as defined in Standard No. ISO 1996-2:2007 [37], determined over all day periods of a year.

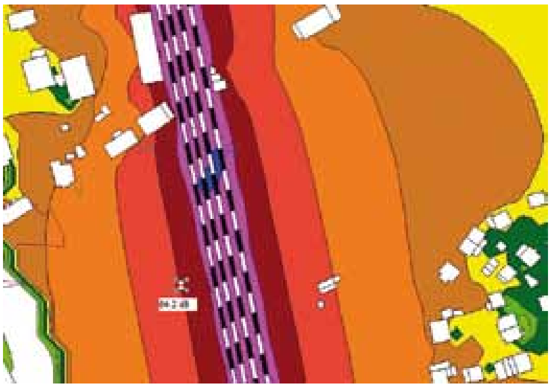

Figure 3. Map L_{day} calculated for a measurement point with SRM II [4]. *Notes.* L_{day}—*A*-weighted long-term average sound level as defined in Standard No. ISO 1996-2:2007 [37], determined over all day periods of a year.

TABLE 6. Comparison of Measured and Computed Quantities for Selected Models (dB)

No.	*P*	L_{d_Ger}	L_{d_Dutch}	L_{d_Nord}	$P\text{-}L_{d\_Ger}$	$P\text{-}L_{d\_Dutch}$	$P\text{-}L_{d\_Nord}$
1	68.6	67.1	64.2	68.2	1.5	4.4	0.4
2	65.7	65.2	59.7	67.1	0.5	6	1.4

Notes. *P*—measured equivalent noise level, L_{d_Ger}—*A*-weighted equivalent noise level calculated with Schall 03 [3], L_{d_Dutch}—*A*-weighted equivalent noise level calculated with SRM II [28], L_{d_Nord}—*A*-weighted equivalent noise level calculated with NMT96 [29].

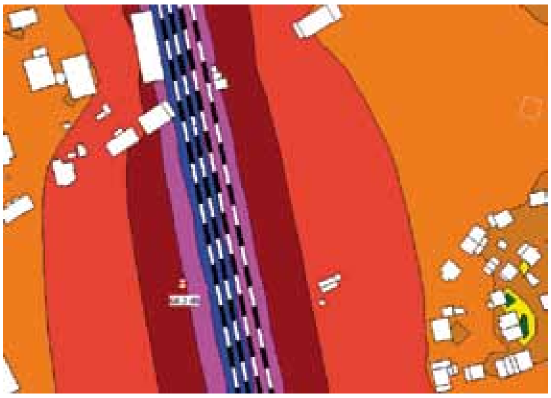

Figure 4. Map L_{day} calculated for a measurement point with the Nordic model [29]. *Notes.* L_{day}—*A*-weighted long-term average sound level as defined in Standard No. ISO 1996-2:2007 [37], determined over all day periods of a year.

To show the difference between these maps, it is essential to assign the same colour range and scale for all models. It is worth mentioning that the results of implementating SRM II differ from the other models.

6.3. Discrepancies in HARMONOISE Reference Data

Predicting noise with IMAGINE [4] is difficult in Poland not just because there is a problem with matching reference data to railways and trains, but also due to the incompatibility of default data. In the documentation of HARMONOISE [3] and IMAGINE, there are a few examples of incompatibilities, e.g., the dependence of the vehicle transfer function ($L_{Hpr,nl,veh}$) and the contact filter function on the diameters of the wheels. The problem resulted from the different set of diameters for these two functions. Only the diameter of 920 mm is common for both functions. Table 7 shows this problem; computations with the default data of IMAGINE are accurate for 920 mm only. Otherwise, input is inaccurate by default.

In this situation, choosing a diameter closest to the functions for default data is correct. For example, if the diameter of a wheel is 660 mm, the vehicle transfer function ($L_{Hpr,nl,veh}$) and the contact filter use 640 and 680 mm, respectively. The situation is the same for 760 mm. If the diameter is 640 mm, there is a vehicle transfer function for such a diameter, but the contact filter has to be for 680 mm. This shows that the reference data are incomplete and can affect accuracy of noise prediction. There are other limitations, too. A parameter called train load is also a problem. It is only for a diameter of 920 mm that there are several high loads available. For other diameters, the load is limited to 50 kN [4]. This can be considered as reference data only, measured during the IMAGINE project. However, this model will be inaccurate in real conditions in individual countries.

TABLE 7. Wheel Diameters for Vehicle Transfer Function and Contact Filter

Diameter (mm)	Vehicle Transfer Function	Contact Filter
360		✓
640	✓	
680		✓
840	✓	
920	✓	✓
1200	✓	

Train classification is a problem, too. The IMAGINE database classifies trains with descriptors, not with actual length or wheel diameter, for example. In this case, a set of values is necessary. Wheel diameter is classified as *small* (<500 mm), *medium* (500–800 mm) and *large* (>800 mm) [4]. Thus 840, 920 and 1200 mm are all in the *large* group, whereas their vehicle transfer functions are different (see Table 7). If these sizes are grouped, they should have one transfer function.

Estimating necessary functions for groups to ensure accurate computations is another problem. Furthermore, in Poland the standard wheel diameter is 940 and 1000 mm for carriages and 1250 mm for locomotives. So it is impossible to have accurate input if reference data of the IMAGINE project are used. The problem with train lengths is similar.

Implementation of IMAGINE poses yet another problem. Train length is often used in estimating the velocity of a train pass-by. Such problems indicate the need to check how these parameters influence the equivalent noise level and determine the level of magnitude.

6.4. Influence of Reference Data on Equivalent Noise Level

If reference data are used, the problems are similar to those discussed in section 6.3. It is then very important how big the differences are between computations for the closest parameters. That is why the eight train types from IMAGINE [4] were simulated. Calculations were performed for 90-m-long trains travelling at 15 m/s. Track conditions were set as wooden sleepers with two rail joints per 100 m of track. Table 8 is an example of calculations for 920-mm-diameter wheels of an NS Mat64 EMU train (Werkspoor/Düwag/Waggonfabrik Talbot, The Netherlands).

Figures 5–8 illustrate disparities between 1200 and 920 mm, and 920 and 840 mm for the eight types of trains. These diameters were chosen because diameters of wheels of Polish trains are within this range. It should be noted that the scales in these figures vary. For 920 and 1200 mm, the maximum difference is 0.25 dB, whereas it is over 2 dB for a similar difference between 920 and 840 mm. So, the inaccuracy resulting from taking the 1200- instead of the 920-mm diameter is several times lower than if the 840-mm-diameter dependent functions are used instead of the 920-mm one. That means taking the diameter closest to the actual one is incorrect. Those results show that there are some specific diameters that generate more noise than similar ones. The same is true for different train types. The differences were smallest for RENFE (DLoco, Spain) and SNCF CC72000 (Alsthom-Atlantique, France) trains. During braking, those differences were much bigger. Calculations showed they ranged from 7.75 dB for a 840-mm diameter to 9.5-dB for a 920-mm one for each type of train discussed in this paper.

Disparity between noise levels for 1200- and 920-mm wheel diameters is quite small (~0.3 dB) in contrast to the differences for 920- and 840-mm wheels. In the context of classifying trains as having *small, medium* or *large* wheels, this is inaccurate. All of those diameters are in the *large* group. Figure 9 shows the gap between maximum and minimum noise level differences for brake types with a 840- and 920-mm wheel diameter. Because the differences between disc and K-block brakes can be neglected (0.001 dB), brakes will be classified as either CI or non-CI, especially that for other conditions (such as in Table 8) the differences in the total noise level are quite small.

7. CONCLUSIONS

This paper briefly describes and analyses some national noise prediction methods. Each is unique and defines the sound source differently. These differences affect noise maps. In Poland, an interim method (SRM II/RMR) for railway noise prediction has been proposed; however, its results are not correct. The main reason is that the Dutch model [28], on which the Polish one is based, assumes lower roughness of the rails than is the case in Poland. This parameter cannot be

TABLE 8. Differences in Equivalent Noise Level for Each Ride Type and Brake Type for 920-mm-Diameter Wheels of an NS Mat 64 EMU Train (Werkspoor/Düwag/ Waggonfabrik Talbot, The Netherlands)

Ride Type	CI	CI–K-block	K-block	Disc–K-block	Disc
Constant speed	92.26839	0.309	91.95898	0.001	91.96040
Idling	92.19019	0.315	91.87495	0.001	91.87640
Acceleration	92.21082	0.314	91.89713	0.001	91.89857
Braking	101.3448	9.519	91.82568	0.001	91.82715
Curving	92.14439	0.319	91.82568	0.001	91.82715
Max–min (without braking)		0.009	—	0.000	—

Notes. CI—cast-iron block-braked vehicles, K-block—K-block braked vehicles, disc—disc-braked vehicles. Green indicates the difference between computations of equivalent noise level for braking cast-iron block-braked vehicles and K-block braked vehicles. This value is omitted in calculating the gap between maximum and minimum noise levels for CI and K-block braked vehicles differences. Grey indicates the modelled equivalent noise level.

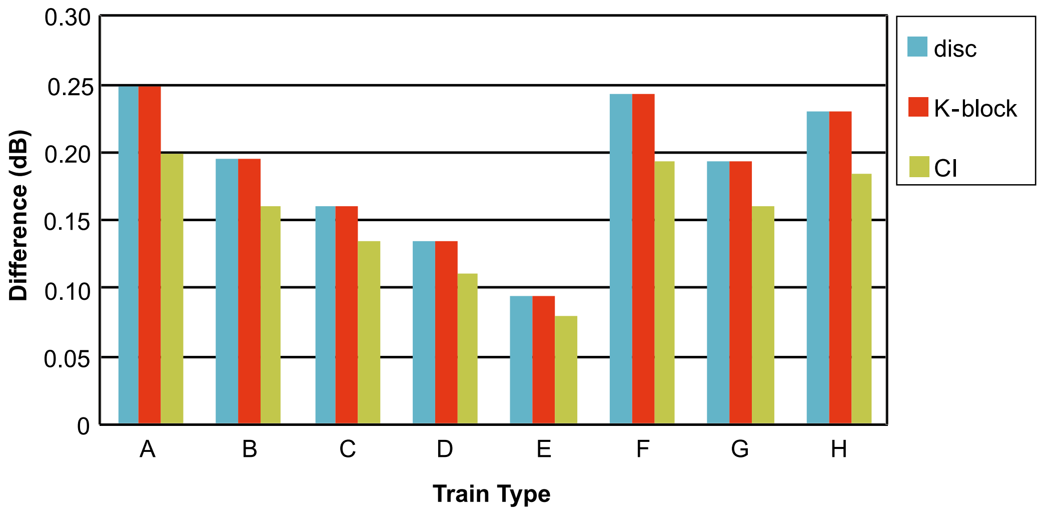

Figure 5. Difference in the equivalent noise level between 1200- and 920-mm wheel diameters for constant speed. *Notes.* disc—disc-braked vehicles, K-block—K-block braked vehicles, CI—cast-iron block-braked vehicles; A—NS Mat64 EMU (Werkspoor/ Düwag/ Waggonfabrik Talbot, The Netherlands); B—NS 1700 (Alsthom, The Netherlands); C—SNCF BB66400 (Vossloh España, Spain); D—SNCF CC72000 (Alsthom-Atlantique, France), E—RENFE (DLoco, Spain); F—NS6400 (MaK/ABB, Germany), G—TKOJ JT 42CWR (EMD, USA); H—DM90 DMU (Duewag/Talbot/SIG, Germany).

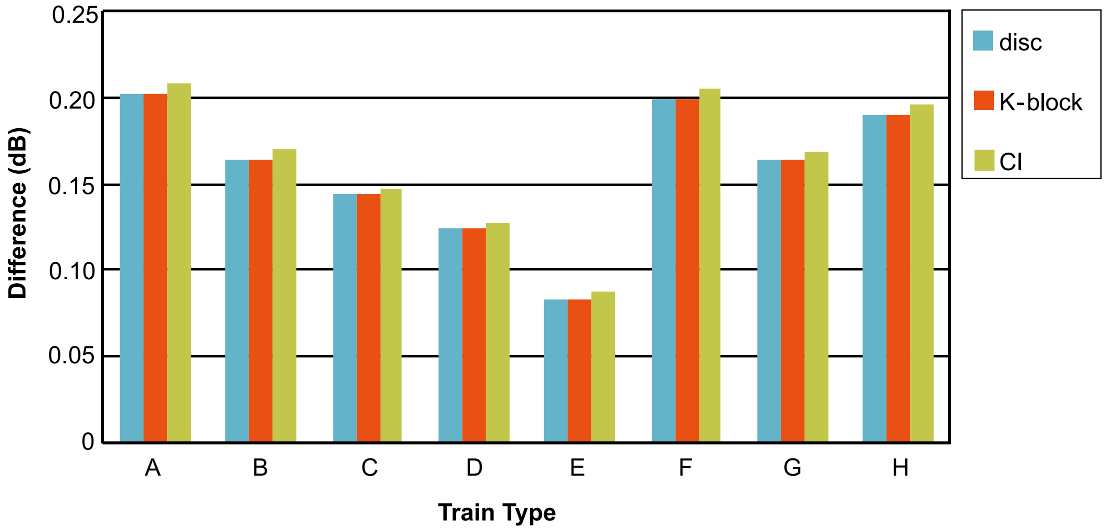

Figure 6. Difference in the equivalent noise level between 920- and 840-mm wheel diameters for constant speed. *Notes.* disc—disc-braked vehicles, K-block—K-block braked vehicles, CI—cast-iron block-braked vehicles; K-block braked vehicles, CI—cast-iron block-braked vehicles; A—NS Mat64 EMU (Werkspoor/ Düwag/ Waggonfabrik Talbot, The Netherlands); B—NS 1700 (Alsthom, The Netherlands); C—SNCF BB66400 (Vossloh España, Spain); D—SNCF CC72000 (Alsthom-Atlantique, France); E—RENFE (DLoco, Spain); F—NS6400 (MaK/ABB, Germany); G—TKOJ JT 42CWR (EMD, USA); H—DM90 DMU (Duewag/Talbot/SIG, Germany).

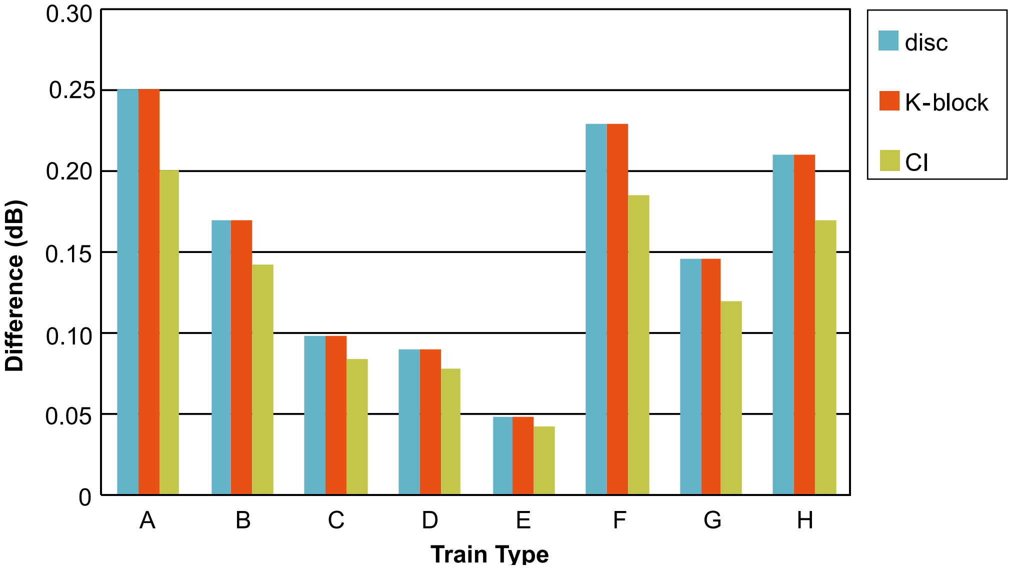

Figure 7. Difference in the equivalent noise level between 1200- and 920-mm wheel diameters for accelerating. *Notes.* disc—disc-braked vehicles, K-block—K-block braked vehicles, CI—cast-iron block-braked vehicles; K-block braked vehicles, CI—cast-iron block-braked vehicles; A—NS Mat64 EMU (Werkspoor/ Düwag/ Waggonfabrik Talbot, The Netherlands); B—NS 1700 (Alsthom, The Netherlands); C—SNCF BB66400 (Vossloh España, Spain); D—SNCF CC72000 (Alsthom-Atlantique, France); E—RENFE (DLoco, Spain); F—NS6400 (MaK/ABB, Germany); G—TKOJ JT 42CWR (EMD, USA); H—DM90 DMU (Duewag/Talbot/SIG, Germany).

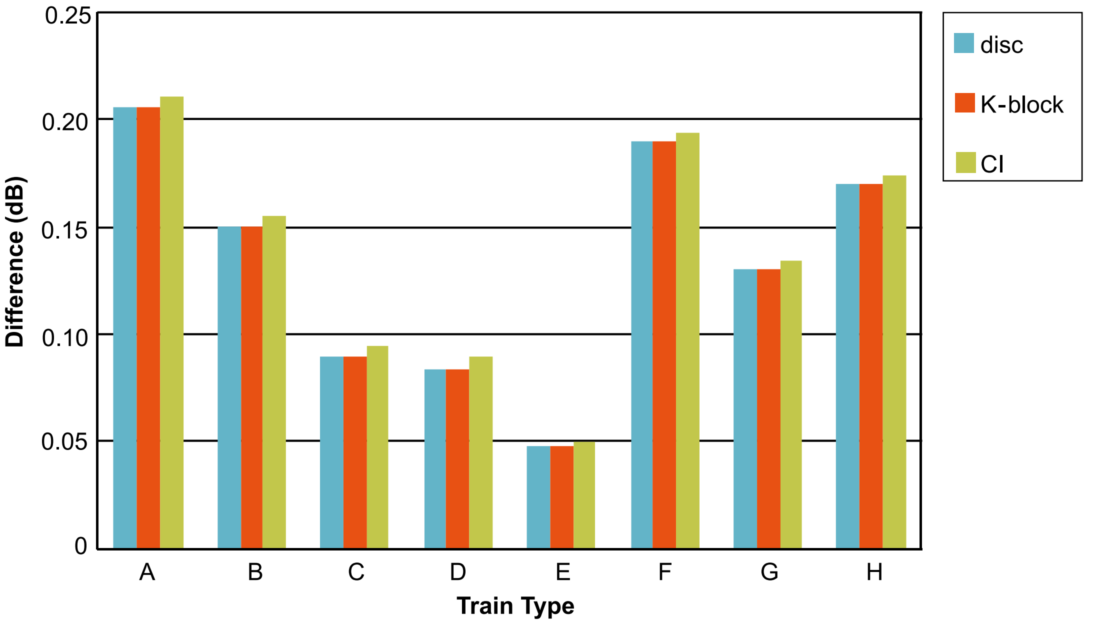

Figure 8. Difference in the equivalent noise level between 920- and 840-mm wheel diameters for accelerating. *Notes.* disc—disc-braked vehicles, K-block—K-block braked vehicles, CI—cast-iron block-braked vehicles; K-block braked vehicles, CI—cast-iron block-braked vehicles; A—NS Mat64 EMU (Werkspoor/ Düwag/ Waggonfabrik Talbot, The Netherlands); B—NS 1700 (Alsthom, The Netherlands); C—SNCF BB66400 (Vossloh España, Spain); D—SNCF CC72000 (Alsthom-Atlantique, France); E—RENFE (DLoco, Spain); F—NS6400 (MaK/ABB, Germany); G—TKOJ JT 42CWR (EMD, USA); H—DM90 DMU (Duewag/Talbot/SIG, Germany).

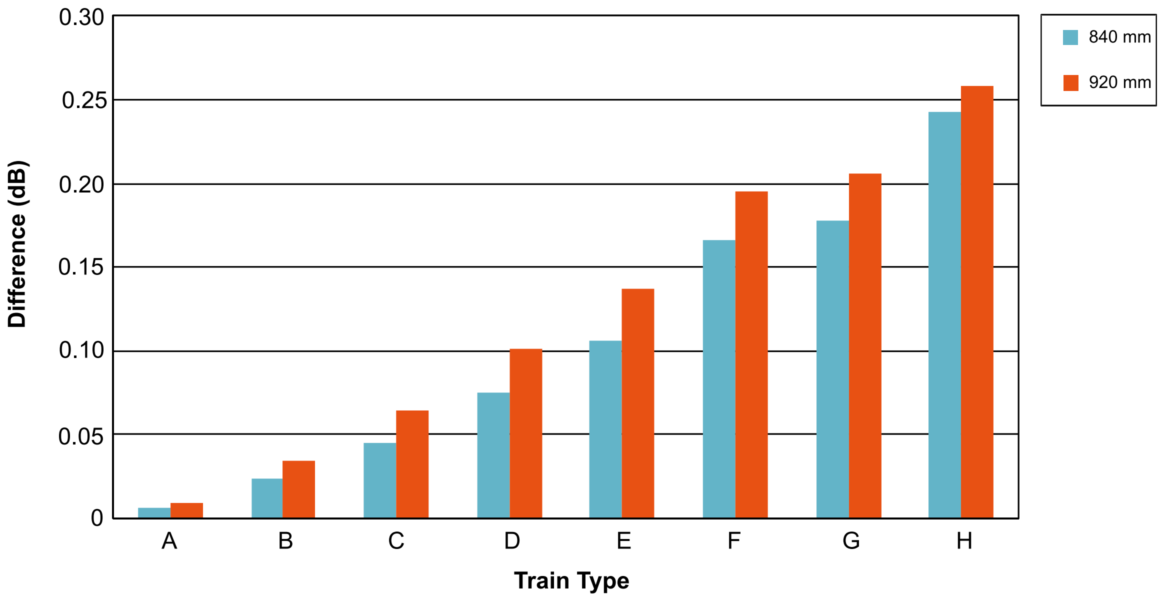

Figure 9. The gap between maximum and minimum noise level differences for CI and K-block brakes with 840- and 920-mm wheel diameters. *Notes.* K-block braked vehicles, CI—cast-iron block-braked vehicles; A—NS Mat64 EMU (Werkspoor/ Düwag/ Waggonfabrik Talbot, The Netherlands); B—NS 1700 (Alsthom, The Netherlands); C—SNCF BB66400 (Vossloh España, Spain); D—SNCF CC72000 (Alsthom-Atlantique, France); E—RENFE (DLoco, Spain); F—NS6400 (MaK/ABB, Germany); G—TKOJ JT 42CWR (EMD, USA); H—DM90 DMU (Duewag/Talbot/SIG, Germany).

changed in modelling, as this is a foundation of this model. Even so, the model was recommended for countries without their own national methods until a common European model is ratified. When railways in Poland are modernized, predicting noise conditions is essential. That is why the HARMONOISE/IMAGINE model [3, 4] was implemented and the problems of real-life application of the noise source method were discussed. In this study, the results of the national and HARMONOISE/IMAGINE models were computed and compared for the Gdańsk area. The IMAGINE results were better than expected, even though only reference datawere used for modelling. Unfortunately, Polish railway conditions differ from those described in IMAGINE, thus the accuracy of this model is limited.

Nowadays, it is impossible to check which country has the lowest noise level and the best practices in noise prevention. HARMONOISE and IMAGINE should have solved that problem, but the flexibility of their solution still requires improvements. A common method is necessary and co-operation of all European countries is essential.

REFERENCES

1. Commission of the European Communities. Communications from the Commission to the European Parliament and the Council. Rail noise abatement measures addressing the existing fleet (COM(2008) 432 final). 2008. Retrieved July 25, 2011, from: http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=COM:2008:0432:FIN:EN:PDF
2. Engel Z, Zawieska WM. The state of protection against noise in the environment in the year of Poland's accession to the European Union. In: 13th International Conference on Noise Control [CD-ROM]. Warszawa, Poland: CIOP-PIB; 2004. In Polish, with an abstract in English.
3. van Beek A, Beuving M, Dittrich M, Beier, Zhang X, Jonasson H, et al. HARMONOISE. Work package 1.2. Rail sources. Task 1.2.1. State of the art (Technical report No. HAR12TR-020118-SNCF10). Paris, Frace: Research and Technology Department, Physics of the Railway System and Comfort; 2002. Retrieved July 25, 2011, from: http://www.imagine-project.org/bestanden/D10_WP1.2_HAR12TR-020118-SNCF10.pdf

4. Dittrich M. IMAGINE. Work package 6. Rail noise sources. IMAGINE railway noise source model, default source data and measurement protocol (IMAGINE report No. IMA6TR-050912-TNO01). Delft, The Netherlands: TNO; 2005. Retrieved July 25, 2011, from: http://www.imagine-project.org/bestanden/IMA6TR-050912-TNO01.pdf
5. Directive 2002/49/EC of the European Parliament and of the Council of 25 June 2002 relating to the assessment and management of environmental noise. OJ. 2002;L189:12–25. Retrieved July 25, 2011, from: http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2002:189:0012:0025:EN:PDF
6. Ustawa z dnia 3 października 2008 roku o udostępnianiu informacji o środowisku i jego ochronie, udziale społeczeństwa w ochronie środowiska oraz o ocenach oddziaływania na środowisko [Act of October 3, 2008, on providing information on the environment and environmental protection, public participation in environmental protection and on environmental impact assessment] Dz U. 2008;(199):item 1227. English translation retrieved July 25, 2011, from: http://www.paiz.gov.pl/files/?id_plik=10611
7. Commission of the European Communities. Commission recommendation of 6 August 2003 concerning the guidelines on the revised interim computation methods for industrial noise, aircraft noise, road traffic noise and railway noise, and related emission data. OJ. 2003;L212:49–64. Retrieved July 25, 2011, from: http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2003:212:0049:0064:EN:PDF
8. Engel Z. From the history of the noise control conference. Arch Acoust. 2010; 35(2):133–44.
9. Gołębiewski R, Makarewicz R. Verification of two methods of railway noise propagation. Arch Acoust. 2009;34(2):177–88.
10. Gołębiewski R, Makarewicz R. Railroad noise affected by downward refraction and turbulence. Arch Acoust. 2002;27:83–94.
11. Thompson D. Railway noise and vibration: mechanisms, modelling and means of control. Oxford, UK: Elsevier; 2008.
12. Janssens MHA, Dittrich MG, de Beer FG, Jones CJC. Railway noise measurement method for pass-by noise, total effective roughness, transfer functions and track spatial decay. J Sound Vibr. 2006;293 (3–5):1007–28.
13. Nilsson C-M, Jones CJC, Thompson DJ, Ryue J. A waveguide finite element and boundary element approach to calculating the sound radiated by railway and tram rails. J Sound Vibr. 2009;321(3–5):813–36.
14. Alberola AJ, Mendoza LJ, Bullmore AJ, Flindell IH. Noise mapping: uncertainties. In: Proceedings of Forum Acusticum, Seville [CD-ROM]. 2002.
15. Manvell D, Stapelfeldt H. Matching noise maps with reality—reducing error through validation and calibration. Ultragarsas. 2003; 2(47):118–22.
16. Probst W. Uncertainties in the prediction of environmental noise and in noise mapping. Acoustique & Techniques. 2005;(40):34–9. Retrieved July 25, 2011, from: http://www.infobruit.com/revues/78_11099.PDF
17. Batko W, Stępień B. Non-parametric methods of estimation of type A uncertainty of the environmental noise hazard indices. Arch Acoust. 2009;34(3):295–303.
18. Calixto A, Pulsides C, Zannin PHT. Evaluation of transportation noise in urbanised areas. A case study. Arch Acoust. 2008;33(2): 185–199.
19. Probst W. Strategic noise mapping—can it serve as a tool in city planning? In: Pawelczyk M, Bismor D, editors. 16th International Congress on Sound and Vibration [CD-ROM]. Krakow, Poland: International Institute of Acoustic and Vibration; 2009. p. 1–6.
20. Kucharski R. Complex noise indicator for noise mapping based on the EU working groups' and Polish results of the annoyance investigations. Arch Acoust. 2007;32(2): 293–302.
21. Czyżewski A, Kostek B, Kotus J. Multimedia interactive services in intelligent environments in multimedia services in intelligent environments. In: Tsihrintzis GA, Lakhmi J, editors. Advanced tools and methodologies. Berlin, Germany: Springer; 2008. p. 275–95.

22. Szczodrak M, Czyżewski A, Kotus J. Investigation of the road noise source employing an automatic noise monitoring station. Arch Acoust. 2008;33(4):77–83.
23. Kotus J, Kostek B. The noise-induced harmful effect assessment based on the properties of the human hearing system. Arch Acoust. 2008;33(4):435–40.
24. Dąbrowski Z, Dziurdź J, Klekot G. Studies on propagation of vibroacoustic energy and its influence on structure vibration in a large-size object. Arch Acoust. 2007; 32(2):231–40.
25. Kompała J, Lipowczan A. Noise hazard to the population of areas connected with functioning of roadway frontier crossings. Arch Acoust. 2007;32(2):279–86.
26. Preis A, Gołębiewski R. Noise annoyance perception as a function of distance from a moving source. Noise Control Eng J. 2004; 52(1):2–25.
27. Czyżewski A, Kotus J, Kostek B. Determining the noise impact on hearing using psychoacoustical noise dosimeter. Arch Acoust. 2007;32(2):215–29.
28. Ministerie van Volkshuisvesting, Ruimtelijke Ordening en Milieubeheer. Reken- en meetvoorschriften railverkeerslawaai ’96 [Calculation and measurement requirements for railway traffic ’96]. 2001. Retrieved July 25, 2011, from: http://www.stillerverkeer.nl/rmv/RMVR/RMVR96.pdf
29. Ringheim M, Nielsen HL. Railway traffic noise—Nordic prediction method (TemaNord 1996-524). Copenhagen, Denmark: Nordic Council of Ministers; 1996.
30. The new German prediction model for railway noise Schall 03 2006—potentials of the new calculation method for noise mitigation of planned rail traffic, in noise and vibration mitigation for rail transportation systems. In: Schulte-Werning B, Thompson D, Gautier P, Hanson C, Hemsworth B, Nelson J, et al., editors. Proceedings of the 9th International Workshop on Railway Noise, 2007. Berlin, Germany: Springer; 2008. p. 186–92.
31. Reiter M, Kostek B. Comparing railway noise prediction results for passenger trains using various models. In: Proceedings. Acoustics 08. 2008. p. 2637–42. Retrieved July 25, 2011, from: http://intellagence.eu.com/acoustics2008/acoustics2008/cd1/data/articles/001148.pdf
32. Reiter M, Kostek B. Implementation problems of IMAGINE noise source model for Polish passenger trains. In: Proceedings of Joint Baltic-Nordic Acoustic Meeting. 2008. Retrieved July 25, 2011, from: http://www.ver.is/bnam2008/Session%20VIII%20Train%20and%20Tram%20Noise/M%20Reiter%20-%20B%20Kostek.pdf
33. Szwarc M, Kostek B. Railway noise problems in Poland. In: 15th International Conference on Noise Control [CD-ROM]. Warszawa, Poland: CIOP-PIB; 2010. In Polish, with an abstract in English.
34. Bolejko R, Dobrucki A. FEM and BEM computing costs for acoustical problems. Arch Acoust. 2006;31(2):193–212.
35. Szczodrak M, Czyżewski A. Software for calculation of noise maps implemented on the supercomputer. Task Quarterly. 2010;13 (3–4):363–77.
36. Czyżewski A, Kotus J, Szczodrak M. Creating acoustic maps employing supercomputing cluster. Arch Acoust. 2010;35(4): 551–64.
37. International Organization for Standardization (ISO). Acoustics—description, measurement and assessment of environmental noise—part 2: determination of environmental noise levels (Standard No. ISO 1996-2:2007). Geneva, Switzerland: ISO; 2007.