Prediction of noise of the stations of the new Budapest metro line M4

F. Augusztinovicz[1], A.T. Fürjes[2], F. Márki[1]

[1] Budapest University of Technology and Economics
Dept. of Networked Systems and Services
H-1117 Budapest, Magyar tudósok krt. 2., Hungary
e-mail: **fulop@hit.bme.hu**

[2] Aqrate Acoustic Engineering Company Ltd.
H-8083 Csákvár, Haraszt u. 15.

Abstract

The stations of the new Budapest metro line M4 are very spacious and the walls are made of highly sound reflecting materials. The environmental authorities have set the requirement that the new stations should be less noisy than the existing ones, but no quantitative target levels were given. The acoustic design went along two parallel paths: the major noise components (moving staircases, ventilation, and rolling of train) were assessed on four typical stations of the already existing Budapest metro lines, and a composite noise level was derived. The expected noise level of the planned stations was calculated by using a commercial room acoustics software package based on geometrical acoustics principles and near-field noise measurements of the new train type. Preliminary calculations have shown that the requirements can only be met if effective sound absorbing materials are applied, at least in the track zone. The paper discusses the optimization of this acoustic lining and compares the predicted levels with measurement results.

1 Introduction

The stations of the new Budapest metro line M4 are substantially different from the stations of the already existing lines 1 to 3. Most of them were built from the surface downwards (by using the so called Milano method) rather than by traditional mining methods, hence their volume is orders of magnitude larger, their shape varies from station to station and the walls are made of smoothed, sometimes painted concrete, tessellated tiles, CorTen (steel) plates or other highly reflecting materials. At the time of their architectural design just very few data on the noise emission of the new trains of type Alstom Metropolis were available. The environmental authorities have set the requirement that the new stations should be less noisy than the existing ones, but no quantitative target levels were given. A further difficulty was raised by the fact that no measuring and/or evaluation method of noise levels of metro stations is available in the local or international standardisation.

The design process of the acoustics of the stations went along two parallel paths. On the one hand the major noise components, such as moving staircases, ventilation on the platforms and arrival and departure of the trains, were assessed on four typical stations of the already existing metro lines M2 and M3. Beside the average noise levels, the typical times of exposure were also determined, and a composite noise level comprising the integral effect of all these components on a hypothetical "average passenger" was derived.

The expected noise level of the planned stations was calculated by using a commercial room acoustics software package based on geometrical acoustics principles. The sound radiated by a test train of the new metro type was measured in free field, and the train was substituted as a set of monopoles of known equivalent sound pressure. The noise of moving staircases were measured on some other stations and modelled as a series of point sources.

The first trial calculations of the expected noise have shown that the predominant noise sources of the new stations will be the rolling trains, and therefore massive noise absorption in the track zone is required. Taking into account both acoustical aspects and a number other characteristics such as combustibility, ageing and contamination damage, an effective sound absorbing material made of expanded glass granules was selected. The absorber plates were placed in the stations below the level of the platform and at both transitions of the station cavity to the tunnel. The exact place of the absorbers was optimized by using a 2D indirect BEM calculation.

The new metro line was put into operation in March 2014. Test runs without passengers but according to the final timetable were performed before, which enabled us to make control measurements in every station. The evaluation of the obtained results shows that the large majority of the new stations are considerably less noisy than any of the investigated stations in use.

The paper reports on the results of the measurement series performed both in the old and the new stations, presents the methods, parameters and results of the prediction calculations, evaluates and compares the finally measured noise levels to the predicted data.

2 Requirements and evaluation methods of the noise of metro stations

There is no maximum allowed noise level prescribed for metro stations in any Hungarian standard or governmental decree [1], and no such limit value exists in the European Union to the best of the authors' knowledge. As a result, in the preparatory phase of planning the new metro line the environmental authorities have set a limitation in relative sense: the new stations should be less noisy than the stations of the existing lines. However, the noise of metro stations poses not only legislative but methodological problems too: while a number of noise components can significantly influence the overall noise of a metro station and their contribution can vary from station to station, no unified evaluation method has been standardized. Therefore, the acoustic design of the station was pursued along two paths. On the one hand an evaluation method had to be developed for metro stations and sufficient data had to be collected on the stations of the existing lines, and on the other the acoustics of the planned stations had to be predicted and trimmed by using a room acoustical modelling and design software package, based on the principles of geometrical acoustics.

3 Noise survey of the noise of existing metro stations in Budapest

Budapest's metro lines were built at rather different times, and their construction, depth and size are rather varied accordingly (see Figure 1.) The lines M2 and M3 have relatively small and uniform stations constructed by mining methods, while the new stations have large volumes of irregular shape. According to a preliminary analysis the potentially dominant partial noise sources of the new stations are the arrival and departure of the trains, a number of moving staircases, the tunnel and station ventilation in normal (and especially in emergency) operating conditions as well as the air compressor and cooling system of the trains. In order to take into account the contribution of all these partial components representatively, we decided to work out an evaluation method which aims to quantify the noise of metro stations from the overall noise exposure of metro passengers' point of view.

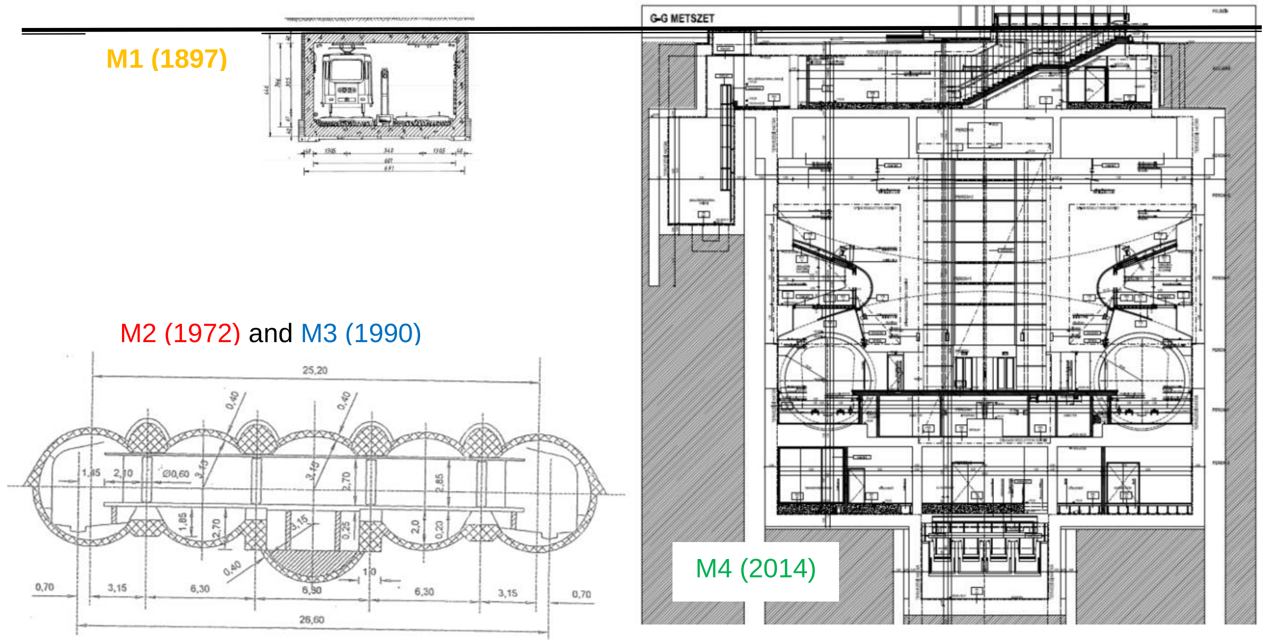

Figure 1: Comparison of typical stations of the four Budapest metro lines
with the finishing year of construction (schematic cross sections drawn to approx. scale)

3.1 Determination of noise of partial sources

	Puskás Ferenc stadion	Batthyány tér	Kálvin tér	Deák Ferenc tér
Travelling on moving staircase	n.a.	71,9/0:68	70,5/0:55	72,1/0:62
Ventilation only on the platform	n.a.	46,5	n.a.	57,2
Moving staircase + ventilation on the platform	60	56,9	59,9	68
Passby of a train, total	74,0/1:25	77,7/1:30	80,6/1:18	80,7/1:28

Table 1: Comparison of level and typical exposure time of partial noise components of the four investigated stations of the existing lines. Sound pressure levels given in dBA, exposure time in m:ss format.

For the sake of this approach not only the average of maximum noise levels of the various components were measured, but the timely variation of each partial noise source and their typical exposure time for the average metro passengers was also recorded. Using an integrating sound level meter and frequency analyser of type Brüel and Kjaer 2250 in logging mode, a time series of equivalent sound pressure levels of 1 s integration time was determined. Based on these data the following partial noise components were derived:

a. equivalent noise level and exposure time acting on passengers travelling on the moving staircase,

b. noise level of the normal ventilation system and other constant noise sources (e.g. the effect of the staircases, transformers and other electric and mechanical sources etc.) on the platform,
c. equivalent noise level of arrival, stationary condition and departure of trains as observed by passengers standing on the platform.

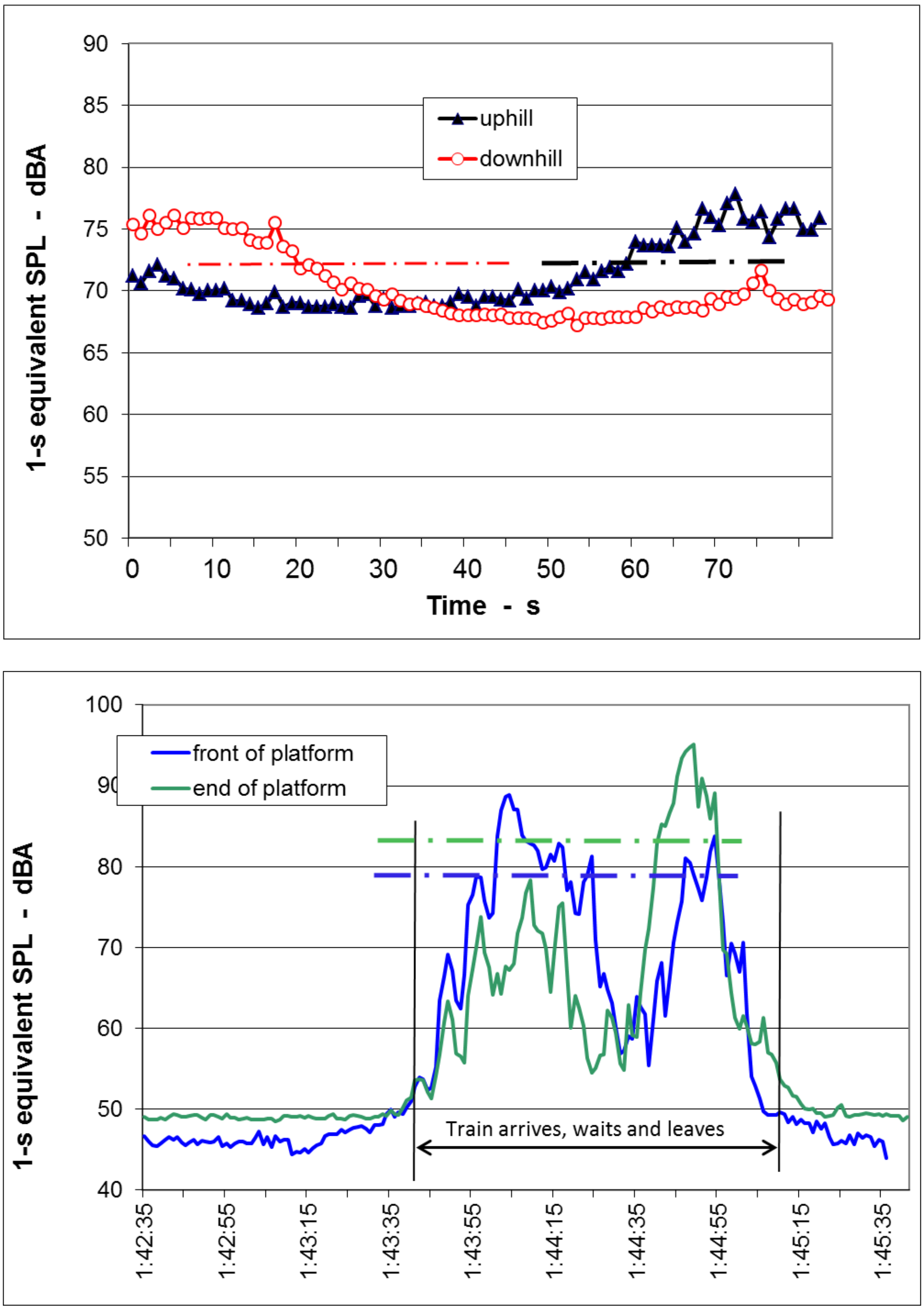

Figure 2: Typical time series of 1-s equivalent noise levels as observed by passengers travelling on the moving staircase (upper diagram) and standing on the platform of Batthyány tér station (lower diagram). Equivalent levels for the total travelling time and for the total arrival, stationary and departure time are denoted by slash-dot lines.

All these measurements were made in very late hours or at downtime of the trains, in order to minimize the background noise effect of steps and talk of passengers. The measurements on the moving staircases were performed and averaged for all staircases of the station; measurements on the platform were repeated in at least 6 points (on the left and right side, at the front, in the middle and at the end of the platform) and averaged arithmetically. Figure 2 shows typical time series of some of the components, while Table 1 summarizes the obtained results of all measurements, performed on the four stations. As can be seen, the two dominant noise sources are travelling on the moving staircase and the train noise, experienced by passengers on the platform. The noise history shows a weak, but non negligible and systematic variation of the staircase noise. The train noise consists of three parts: the arrival and departure is approx. equal in time (between 30 to 40 s) but considerably different in level, depending on the point of observation. The time of stationary section depends on the time requested for passenger exchange, typically between 20 to 35 s.

3.2 Derivation of a representative overall noise level of stations

The notion of "overall" or "average" noise level is based on the noise dose, experienced by an average user of the station. His/her exposure, as shown in Figure 3, is made up of three components: travelling on the moving staircase(s), waiting on the platform for the arrival of the train and the arrival of the train. (It can happen of course that the passenger arrives on the platform when the former train is just leaving the station, but it is also possible that he/she just arrives at the moment when the doors are open. The expected value of the waiting time on the platform is therefore half of the average time gap between two consecutive trains, plus an arrival's time.)

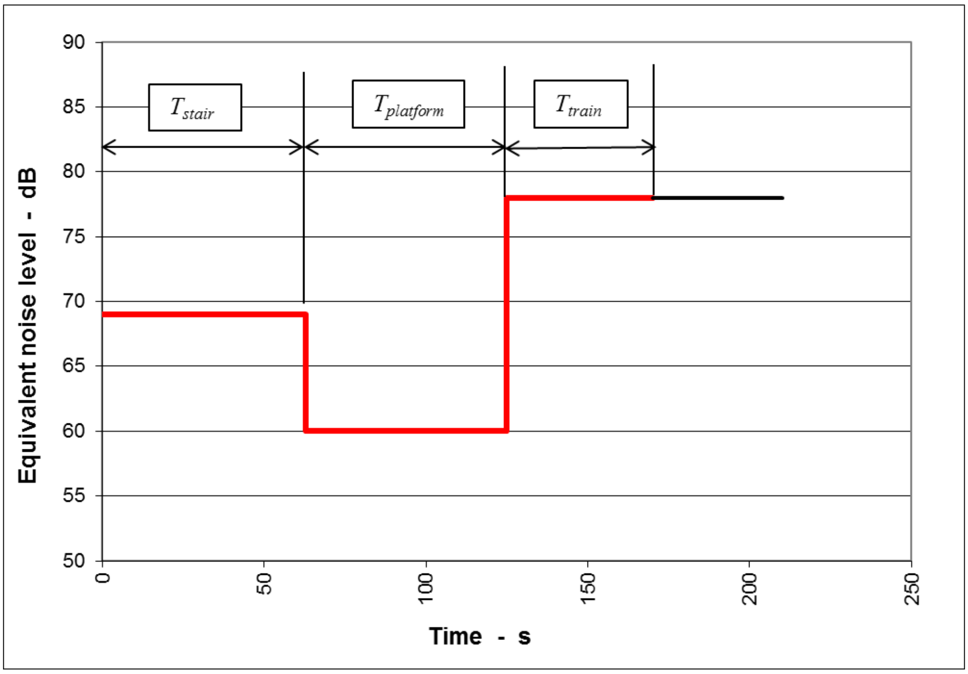

Figure 3: Schematic representation of the noise exposure of a passenger

The overall exposure level is calculated then by the formula

$$L_{overall} = 10\log\frac{T_{stair}\times 10^{L_{stair}/10} + T_{platform}\times 10^{L_{platform}/10} + T_{train}\times 10^{L_{train}/10}}{T_{tair} + T_{platform} + T_{train}} \tag{1}$$

Taking into account the timetable of the new line and typical arrival and departure times of the Alstom trains the calculation error is acceptable if all the three partial exposure times are assumed to be 60 s. (1) then takes the form

$$L_{overall} = 10\log\frac{10^{L_{stair}/10} + 10^{L_{platform}/10} + 10^{L_{train}/10}}{3} \qquad (2)$$

Trial calculations have been performed for the four investigated stations, and the obtained results are the following:

	Puskás Ferenc stadion	Batthyány tér	Kálvin tér	Deák Ferenc tér
Moving staircase, L_{stair}	72	71,6	72,6	73
Waiting, $L_{platform}$	54,4	56,7	61,1	67,5
Train, L_{train}	74,2	79,2	82,9	81,3
Overall level according to (1)	**71,1**	**74,4**	**77,7**	**76,5**
Overall level according to (2)	**71,5**	**75,2**	**78,5**	**77,3**

Table 2: Results of trial calculation of the overall noise level for four stations

As can be seen, the error caused by neglecting the real exposure times of partial components is negligible with respect to the accuracy and the applied assumptions and approximations of the suggested method.

4 Prediction of station noise by means of a ray tracing technique

The commercially available software tools for modelling architectural acoustics are based on principles of geometrical acoustics with varying enhancements to approximate phenomena of non-geometric nature. This is reasonable, since in architectural scales sizes of sources are not relevant, but their far-field directional behaviour is well described, and because wave field is assumed to be linear and time-invariant.

When trying to overcome limitations of geometric models, one will face the problem of describing architectural conditions (absorption, scattering) and source characteristics in simple and practical forms.

4.1 Generation of input data for the calculations

According to the measurements as reported above, the predominant noise sources of the Budapest metro stations are the rolling stock, moving staircases and – less importantly – the ventilation system.

The applied ray tracing program, EASE 4.3.9 with Aura module [3], is renowned for its stability in prediction of architectural acoustic parameters. Basically EASE is meant to be used to model loudspeaker systems so it can handle only point sources, but each point source can have its own directional characteristics. In our case, no directional data was available. Also the size of the source is not negligible, so we assumed that all types of noise sources can be described by monopoles and the geometry of nearby reflecting surfaces.

Also, EASE is not meant to model moving sources, so the train passing by was modelled by distinct phases (arriving, roll by, departure).

The source model of the train assumed in the geometric acoustic model consisted of the geometry of the body of the vehicle (acoustically reflective and non-diffuse, except for the bottom face) and the assumed positions of known partial sources of noise (see Figure 4).

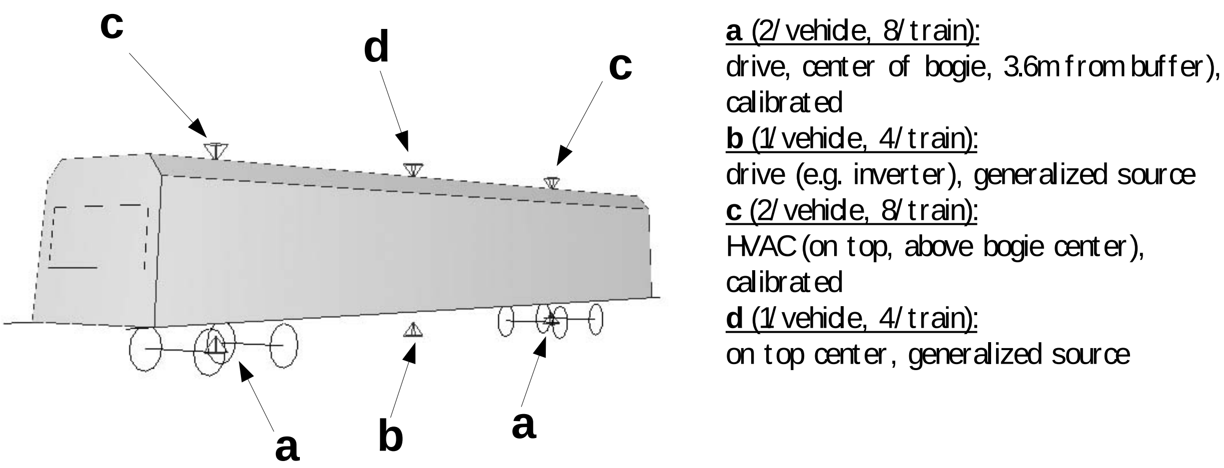

Figure 4: Generalized model of a single vehicle of the train.

The idea was to find the sound pressure levels for each source component at each frequency band to gain the best matching results to what was measured under controlled conditions (see 4.1.1. below).

After a direct comparison of measured data at different positions of a passing by vehicle, we have selected to use only a (bogie) and c (HVAC unit). As EASE describes single point sound sources by the free-field, far-field SPL calculated at 1 m distance, the results of the best matching spectra are shown in Figure 5. Note that EASE handles frequencies in 1/3 octave band resolution from 100 Hz to 10 kHz. Bands below 100 Hz were assumed to have the same transfer function from source to receivers.

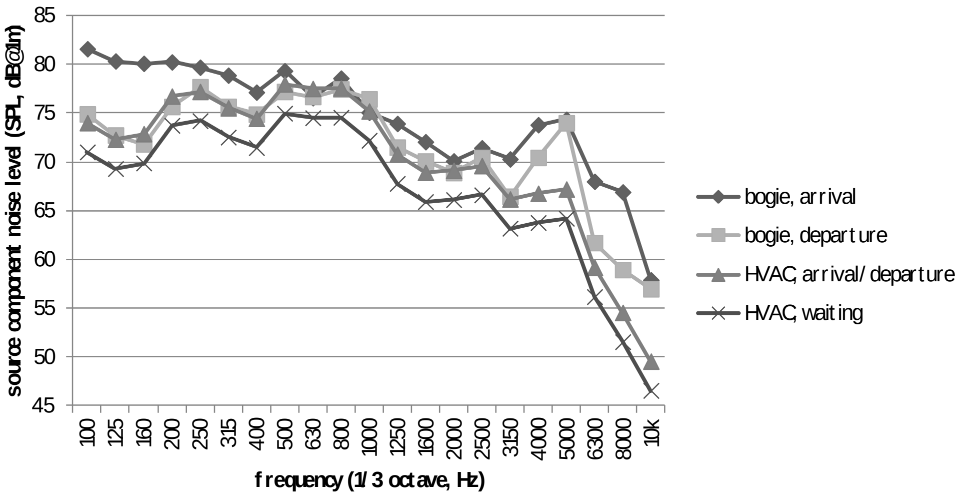

Figure 5: Noise levels of the vehicle noise components best matching to measured total levels of arrival, departure and waiting situations.

Moving staircases were substituted by a series of incoherent point sources and confirmed that if sources are positioned at 3 m distances, their resulting far-field will produce only insignificant error (see Figure 6). Thus the number of monopoles used for each staircase was simply the length of the staircase divided by 3 m.

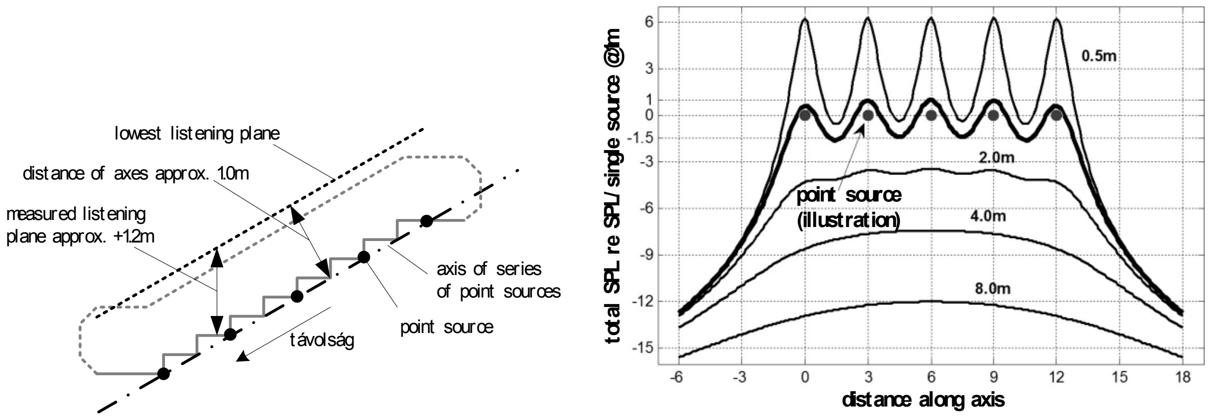

Figure 6: A series of monopoles is used for modelling of the moving stairs.

Since there were no installed samples of the moving stairs, we used the spectral envelope of the measurements at an older, existing moving stairs and scaled them to the bidding requirement of 60 dB L_{Aeq}.

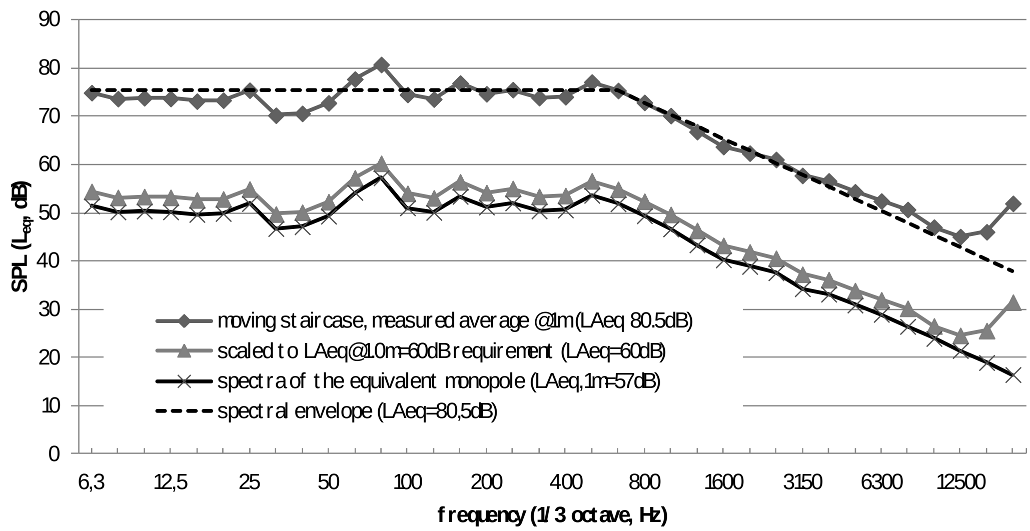

Figure 7: Derivation of the sound pressure level spectra of the monopoles used for the moving staircases.

Ventilation noises were also modelled by monopoles. Derivation of equivalent sources is illustrated in Figure 8. Noise levels and spectra of monopoles of the ventilation system were calculated from the source data of the manufacturer and the effects of the ducting and silencers, as calculated by the designer [4].

4.1.1 Measurement of train noise

The supplier of the train has provided the noise test report, performed according to the prescriptions of the international standard for exterior noise emission [5] but, unfortunately, these values were inappropriate for our calculations for a couple of reasons. The standard prescribes the measurements for constant speed, which is very much different from the operating conditions of a metro train entering and leaving the station. The prescribed measuring distance is 25 m from the track and at 3,5 m above the rail head, while the passengers stand at just a few meters from the train in the station. Therefore, a measurement series was

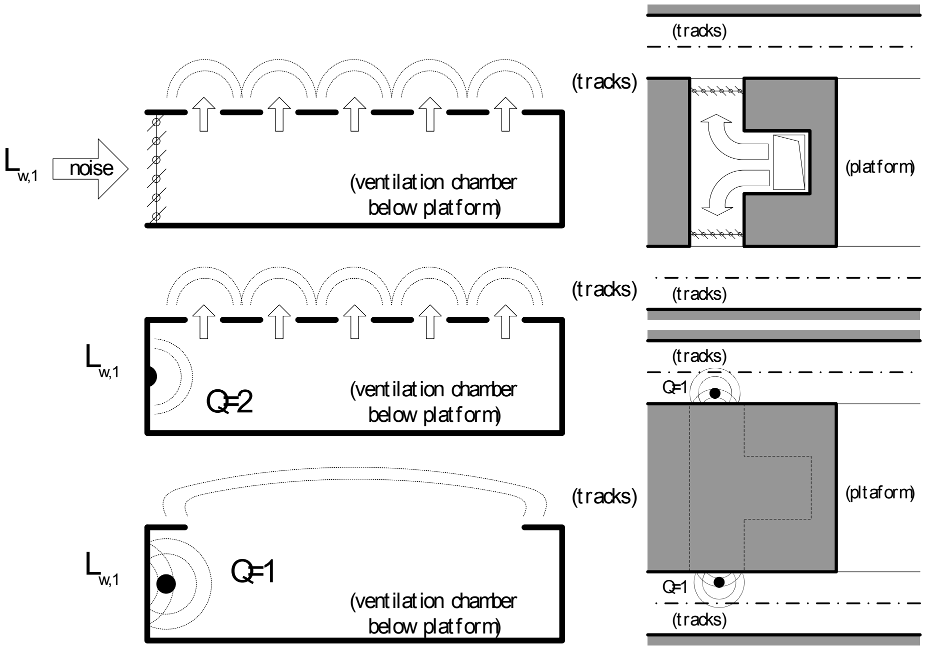

Figure 8: Derivation of equivalent source models of ventilation.
Left: horizontal section below platform. Right: Horizontal section at the end of platform.

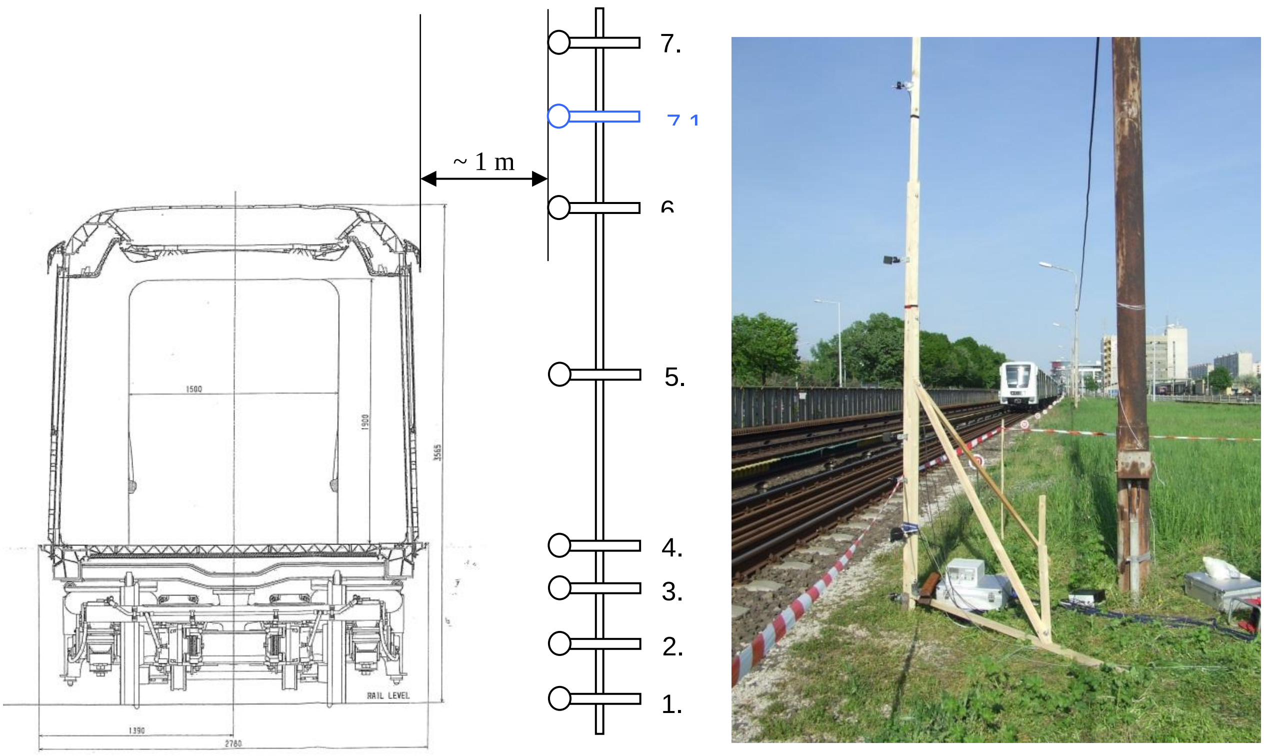

Figure 9: Measurement setup by using 7 microphones, used to determine the source strength of the equivalent monopoles of the train under simulated normal operating conditions:
breaking from normal speed to stationary and start to normal speed.

performed in free field, at 1 m distance from the sidewall of the carriages, rolling on a test track in free field by using a microphone boom of 7 microphones, see Figure 9. The obtained equivalent noise levels averaged for a full arrival (breaking) and departure (acceleration) event for the relative position of the stopping train as if the microphone boom were set up at the beginning, in the middle and at the end of the platform are summarized in Table 3 below.

Averaged arrival, measured at the end of platform, in direction A	87.7
Averaged arrival, measured at the end of platform, in direction B	86.6
Averaged arrival, measured in the middle of platform, in direction A	84.5
Averaged arrival, measured in the middle of platform, in direction B	84.2
Averaged acceleration, measured at the end of platform, in direction A	86.5
Averaged acceleration, measured at the end of platform, in direction A	86.4

Table 3: Equivalent noise levels, measured of arriving and departing trains in dBA in directions A and B by mic #2, as if was sensed by a hypothetical observer at the beginning, in the middle and at the end of the platform

The obtained noise spectra, used to calibrate the source characteristics are depicted in Figure 5. above

4.2 Station noise level prediction by using geometric acoustics modelling

As described above, we used a conventional, commercially available room acoustics modelling software [3] to predict noise levels in the station at positions where the passengers might be exposed.

4.2.1 Station geometries

The geometric models were created by using available architectural data. Tunnels were assumed to have a perfect absorbing ending and at least 80 m length at each end so that the train could be modelled in different positions. One of the 10 developed geometric models is illustrated in Figure 10.

Properties of surfaces were estimated or taken from manufacturer certificates. Actually all surfaces, except for the materials we assumed to be placed for noise control, could be taken as acoustically reflective and non-diffusing (concrete, glass, steel plates, etc.). Absorption characteristics used for the prediction calculations are shown in Figure 11.

4.3 Evaluation of prediction results

Room acoustics models using assumptions, materials and equivalent sources were modelled in different situations of the train (arriving in tunnel, arriving halfway in the station, waiting in the station, departure halfway in the station and departure in tunnel). Results were gathered as room acoustic transfer functions for each octave band for each listening position. Eventually, we added calculated equivalent source noise levels for each modelled position of the train and summed their effects, weighted according to their exposure time.

Final results were collected in an excel sheet, where each source of noise (train on the left or right track, moving staircases each, transformer, ventilation) could be switched on and off, and results were illustrated as the distribution of the total A-weighted sound pressure levels along the platform and on the staircases.

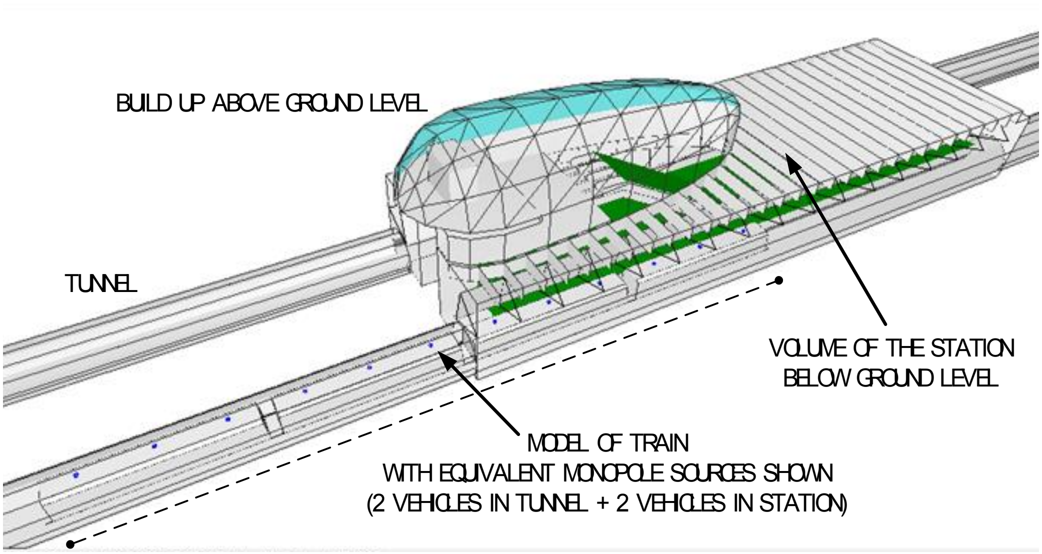

Figure 10: Geometric model of the station Bikáspark

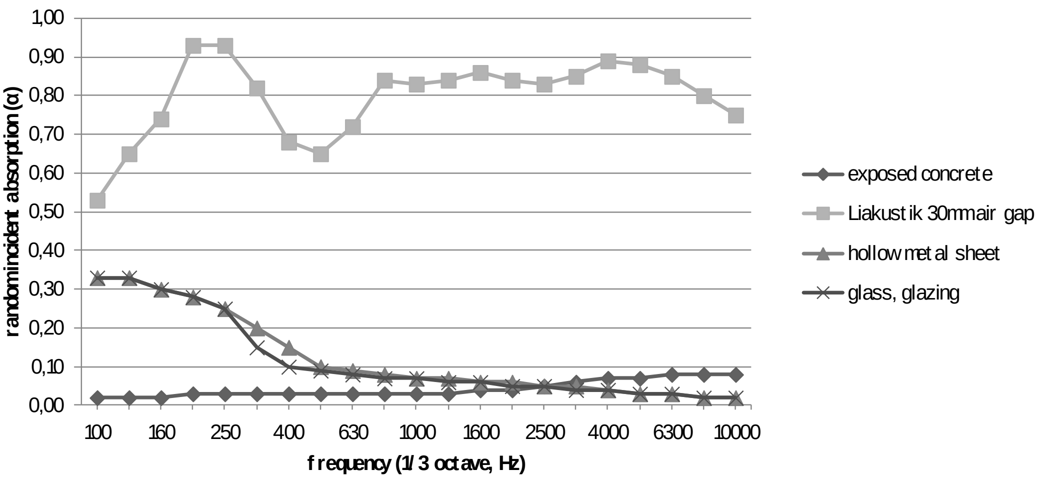

Figure 11: Absorption characteristics of materials assumed for calculations in the architectural model.

Figure 12. illustrates the potential positions of acoustic absorbers together with the cross section of the train, which were calculated as possible "scenarios". Each combination was evaluated by a single number as the change in average noise level across the whole platform relative to the initial configuration. The initial configuration included one single absorbing surface below platform level (position A). Modelled scenarios for the station shown in Figure 10 as well as noise level reduction expressed as the change in average noise level, and also the effectiveness of absorption expressed as the noise level change per 100 m^2 of absorptive surface are summarized in Table 4.

As can be seen, the maximum noise reduction with respect to the 'no absorber' case could be achieved by using all possible absorber surfaces from A to E, resulting in more than 10 dBA difference. The most effective position is clearly surface A followed by B, if only sources under the floor of the carriages are considered. Not surprisingly, for the HVAC system placed on the roof of the carriages positions C and D are the most useful and effective.

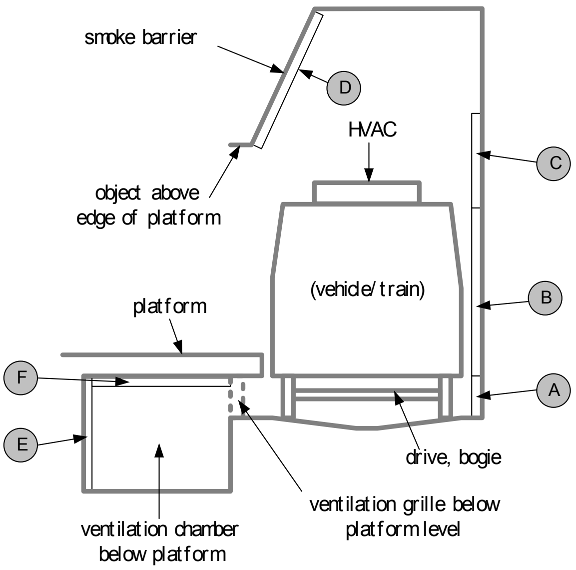

Figure 12: Cross section of a track showing suggested positions of sound absorbing materials.

description of scenarios			identification of calculations									
description	addition	area of absorption	**TET-01**	TET-01X	TET-01B	TET-01C	TET-01D	TET-01E	TET-01F	TET-01BD	TET-01BC	TET-01BCD
initial configuration (Liakustik below platform level)	A	301 m²	O	-	O	O	O	O	O	O	O	O
10m of tunnel wall is absorbing at each end	-	401 m²	O	O	O	O	O	O	O	O	O	O
along station, absorbing material above platform level	B	399 m²	-	-	O	-	-	-	-	O	O	O
along station, absorbing material above the train roof level	C	399 m²	-	-	-	O	-	-	-	-	O	O
smoke barrier facing the train is absorbing	D	751 m²	-	-	-	-	O	-	-	O	-	O
below platform, ventilation chamber wall is absorbing	E	367 m²	-	-	-	-	-	O	-	-	-	-
below platform, ventilation chamber ceiling is absorbing	F	393 m²	-	-	-	-	-	-	O	-	-	-

	modelled scenarios								
	TET-01X	TET-01B	TET-01C	TET-01D	TET-01E	TET-01F	TET-01BD	TET-01BC	TET-01BCD
noise source	change relative to initial configuration TET-01								
bogie, SW	3,19	-2,83	-1,98	-2,54	-0,32	-0,31	-4,15	-4,25	-5,13
HVAC, SW	0,94	-1,56	-2,72	-3,75	-	-	-4,90	-4,02	-5,95
track ventilation, W	-	-2,60	-	-	-	-	-	-	-4,74
station ventilation	-	-	-	-	-6,71	-6,28	-	-	-7,41
noise source	effectiveness of absorption (dB/100m²)								
bogie, SW	1,06	-0,71	-0,50	-0,34	-0,09	-0,08	-0,36	-0,53	-0,33
HVAC, SW	0,31	-0,39	-0,68	-0,50	-	-	-0,43	-0,50	-0,38
track ventilation, W	-	-0,65	-	-	-	-	-	-	-0,31
station ventilation	-	-	-	-	-1,83	-1,60	-	-	-0,48

Table 4: Overview of modelled noise control scenarios (upper part) and summary of results (lower part) for the Bikáspark station. Note: SW means ‘train from south-west’, W means ‘track ventilation below platform facing west’.

5 Noise reduction by sound absorbing material in the track zone

Taking into account both acoustical aspects and a number other characteristics such as combustibility, ageing and contamination damage, an effective sound absorbing material made of expanded glass granules, named Reapor, was selected by the investor and the architects of the stations. Unfortunately, financial limitations allowed to use it only in positions A, E and under platform level between the ventilation grilles. Its absorption vs. frequency curve is very similar to Liakustik, depicted in Figure 11.

The placement in positions under the platform and in E were realized by a special cement. However, the geometry of the stations allowed to vary the exact position of the material on surface A: apart from gluing it to the station wall, a certain air gap behind the absorbing plate was also possible. In order to determine the optimum distance from the wall, a two-dimensional BE model was developed and the expected sound pressure levels were calculated for a hypothetical, vertical field point mesh. The obtained results are depicted in Figure 13. One can conclude that the optimal place of the absorber is about in halfway between the concrete wall and the carriage: then the back side of the plate can also act as an effective absorber, but the space around the bogies is not too confined.

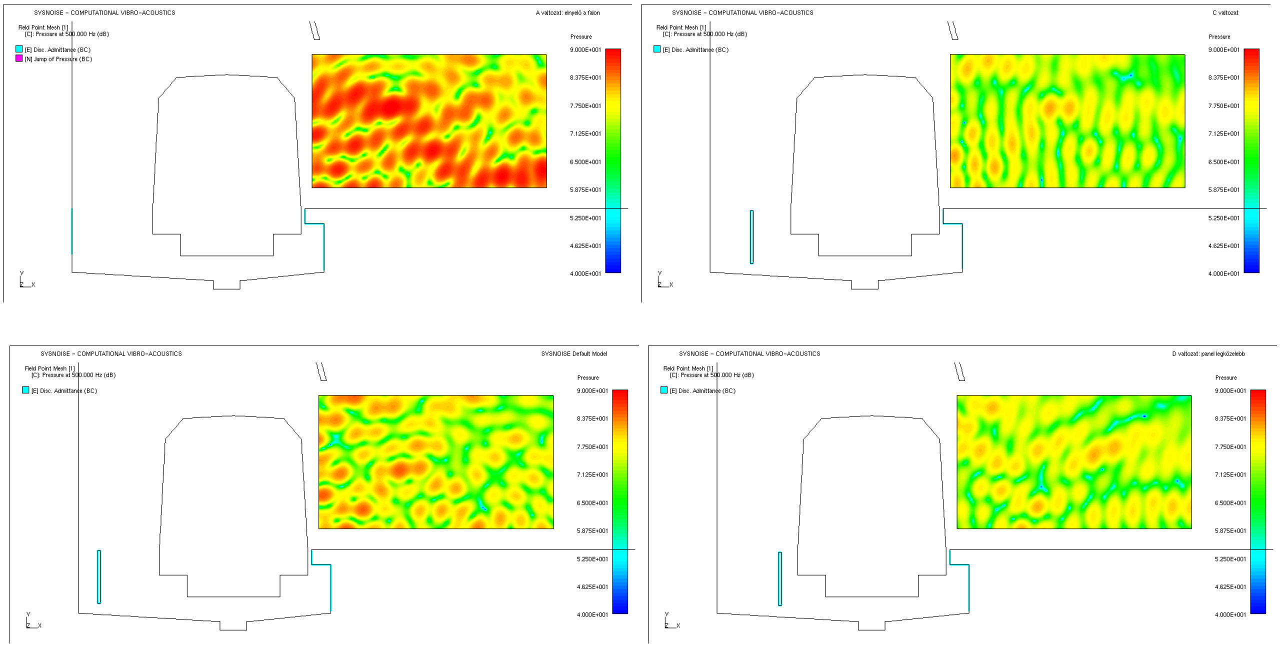

Figure 13: Sound pressure levels calculated by means of an incirect 2D boundary element model for 500 Hz with varied placement of the sound absorber plate (denoted by thick turquoise lines) in the track zone. Colour code from blue to red corresponds to 50 dB range.

6 Control measurements

After having started the test runs we were asked to perform control noise measurements in the new stations, based on the method as described in 3.2. above. The results are summarized in Table 5, where some further partial components beyond the dominant ones are also given. One can say in general that the gained overall levels are relatively low. The average value is less than 71 dBA, which equals to the overall noise level of the least noisy station Puskás Ferenc stadion of line M2, and all new stations are less noisy than any of the three other stations investigated. The ventilation systems of the new stations are decidedly quieter than the old ones, but the moving staircases considerably exceed the expected noise figures. The predominant noise source of all new stations is however the train passby, in the average 8 dBA above the total platform noise including ventilation, surface traffic and the infiltrating effect of the moving staircases. Next to the trains travelling on the moving staircases is another important contributor to the total noise exposure of passengers.

Stations	Travelling on the moving staircase	Ventilation	Moving staircase on the platform	Surface traffic	Platform, total	Trains' passby	**Overall**
Kelenföld állomás	69,5	53	64,8		65,1	71,2	**69,3**
Bikáspark	67,3	56,9	60,0		61,7	74,3	**70,5**
Újbuda	67,3	49	60,0	52,3	61,0	70,1	**66,2**
Móricz Zs. körtér	71,7	56,4	65,4	52,3	66,1	67,6	**69,1**
Szent Gellért tér	74,4	45,7	60,8		60,9	75,6	**73,4**
Fővám tér	74,7	54,6	65,5		65,8	76,2	**74,0**
Kálvin tér	71,8	55,9	67,1		67,4	73,4	**71,5**
Rákóczi tér	72,2	54,7	63,7		64,3	74,5	**72,0**
II. János Pál tér	73,4	50,3	64,4		64,6	72,5	**71,5**
Keleti pályaudvar	71,4	59	67,7		68,2	72,8	**71,2**
Average	**71,4**	**53,6**	**63,9**	**52,3**	**64,5**	**72,8**	**70,9**
Standard deviation	2,6	4,1	2,8	0,0	2,6	2,6	2,2

Table 5: Summary of control noise measurements of stations of the new metro line, in dBA, based on the method as described in Chapter 3.2. above.

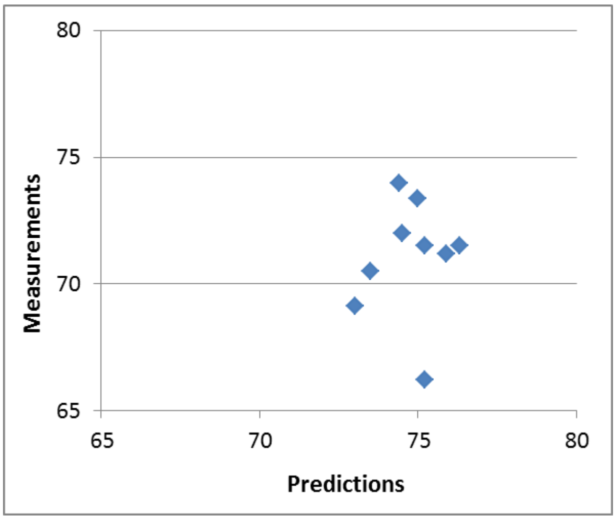

Figure 14: Comparison of predicted and finally measured overall noise level of the new stations, in dBA.

It is also worth comparing the predicted and finally measured noise levels for the ten new stations. Apart from one dropout value (most probably caused by limited train speeds at the time of measurements) the accuracy of the predictions is reasonable, with approx. 3 dBA overestimation with respect to the actually measured values.

7 Conclusions

The paper concentrates on two novel approaches of evaluation and prediction of noise of metro stations:

– development of a composite noise level, based on the noise exposure of passengers having resort to the station at issue; and
– adoption of a room acoustical analysis tool, originally developed to calculate sound field parameters in rooms generated by loudspeakers, for complex and moving noise sources such as metro carriages and moving staircases.

The prediction method, extended by a 2D BE calculation step, was used to determine optimal configuration of the sound absorbing lining of stations. This optimal combination was not realized for financial reasons. Even so, the stations of the new line are definitely quieter than the stations of other metro lines in Budapest.

References

[1] *Ministerial decree No. 8/2002. (III. 22.) KöM-EüM on the establishment of noise and vibration limit values.* (In Hungarian, in effect at the time of the reported investigations. Current version: 27/2008 KvVM-EüM)

[2] Z. Sü and M. Çalıskan, *Acoustical design and noise control in metro stations: Case studies of the Ankara metro system.* Building Acoustics, Vol. 14. No.3. pp. 231-249 (2007)

[3] Simulation software package *EASE*, Version 4.3.9.

[4] *Acoustic expertises of the ventilation system of stations of the metro line M4.* Constans 2000 Ltd., Budapest (2010-2011) (In Hungarian)

[5] ISO 3095:2005 *Railway applications - Acoustics - Measurement of noise emitted by railbound vehicles* (Currently valid version: ISO 3095:2013)