BNAM 2021
Baltic-Nordic Acoustics Meeting
3rd-5th of May, Oslo, Norway

The correlation between outdoor and indoor vibrations from metro trains in Oslo

Sigmund Olafsen
Brekke og Strand akustikk, P.O.Box 1028, NO-0218 Oslo, Norway, so@brekkestrand.no

The increasing population of Oslo has led to an increasing demand for metro traffic. It is important to avoid annoyance due to vibrations from these metro trains. Thus it is crucial to determine the level of vibrations transmitted into residences near the track. Correct prediction of transmission of vibrations from a metro track into a house close to the line is a very difficult challenge. A simple way of reliably predicting vibrations inside a house based on measurements of the vibrations on the ground outside the house would be very desirable. This paper will present results of measurements outside and inside houses. Many of the measurements were made during systematic control measurements along the recently rehabilitated metro lines Østensjøbanen and Kolsåsbanen in Oslo and neighbouring Bærum. Measurements have been made outside the house on the ground and usually at each level in the house, often in the basement, at ground level and on the first floor. This paper will present results based on vw,95 in three dimensions. It would seem that indoor vibrations from metro trains are usually lower than those measured on the ground outside the house.

1 Introduction

There is an increasing need for reliable prediction of vibration levels from metro lines into buildings. The most common case is to check whether a planned residential building will have excessive vibration according to local regulations [1]. It is usually not practical to do a sufficient analysis of ground conditions and building structure to achieve acceptable accuracy of the predictions. The approach suggested in this paper is purely empirical. Measurements have been made on the ground outside and on the floor inside in 90 houses with triaxial transducers, geophones or accelerometers depending on conditions on site. Measurements have been performed twice in 11 of these houses, usually before and after upgrading of the track. A subset of these data have been published earlier [2]. In this present paper the data presented are divided by floor levels. 57 cases of outdoor vs. basement, 80 cases of outdoor versus ground floor and 84 cases of outdoor vs. 1st floor are included. Most of the measurements have been made with 5 triaxial transducers.

2 Method

The measurements have been made with a combination of geophones and accelerometers. The geophones are Norsonic 1290’s, the accelerometers are PCB 365b18’s. Most of the reported outdoor measurements are made using the geophones. With appropriate setting of sensitivity and range they give a practical noise floor of around 0,001 mm/s for metro vibrations. The accelerometers have a practical limitation of around 0,01 mm/s.

The geophones have been used for outdoor measurements and for measurements on hard floors. They cannot be used on all types of floor due to the spikes that might leave a permanent mark after the measurement. The accelerometers were used on softer floors.

The analyser used is an OROS 36, for some of the older measurements fitted with 12 channels. Later measurements were made with the analyser equipped with all 16 channels in use.

All the metro trains in Oslo are of the same type, Siemens MX-3000. They are also of roughly the same age, delivered during the years 2006-11. The metro runs on separate double tracks without interference from other traffic. The trains have very little variability in the driving patterns. Normally around 20 events have been measured at each site.

The measurements have been made in houses along the metro lines Østensjøbanen (rehabilitated 2014-16) and Kolsåsbanen (rebuilt from a tram line that was closed in 2006, the metro line gradually opened in stages, completed 2014). There are also measurements that were made in response to complaints from neighbours.

The measured values have been analysed according to NS 8176 [1]. This gives single values for a series of vibration measurements which is expected to be exceeded for 5% of the train passages.

Directions are defined as follows:

X is horizontal perpendicular to the track

Y is horizontal along the track

Z is vertical

3 Results

The results have been shown as outdoor vs. indoor measurements for the cases that are sufficiently well represented in our data:

Correlation between directions outdoors

Outdoor vs. basement indoor vibrations

Outdoor vs. ground floor indoor vibrations

Outdoor vs. 1st floor indoor vibrations

3.1 Correlation between direction outdoors

Our results indicate that the ratio between the directions on the ground are almost constant. This result is surprising as the ground conditions vary widely between the sites where measurements have been made. The result has gone unnoticed in earlier publications about metro vibrations [2,3,4]. The correlations given in table 1 are two-way correlations. Three-way correlations are slightly different.

Table 1: Ratio between vibration in outdoor directions

Direction	Relative to x	Correlation (r^2)
Y	0,9234	0,9778
Z	0,5169	0.8572

There are few cases of substantial deviations from the factors. This means that measurements of vertical vibrations give a reasonable indication of outdoor vibration levels. The horizontal vibration level outdoors is usually a little less than twice the vertical vibration level.

3.2 Outdoor vs. basement vibrations

A plot of measured vibrations in the direction with the highest vibration level is shown in figure 1. This plot shows the magnitude of weighted vibration outdoors versus weighted vibration indoors.

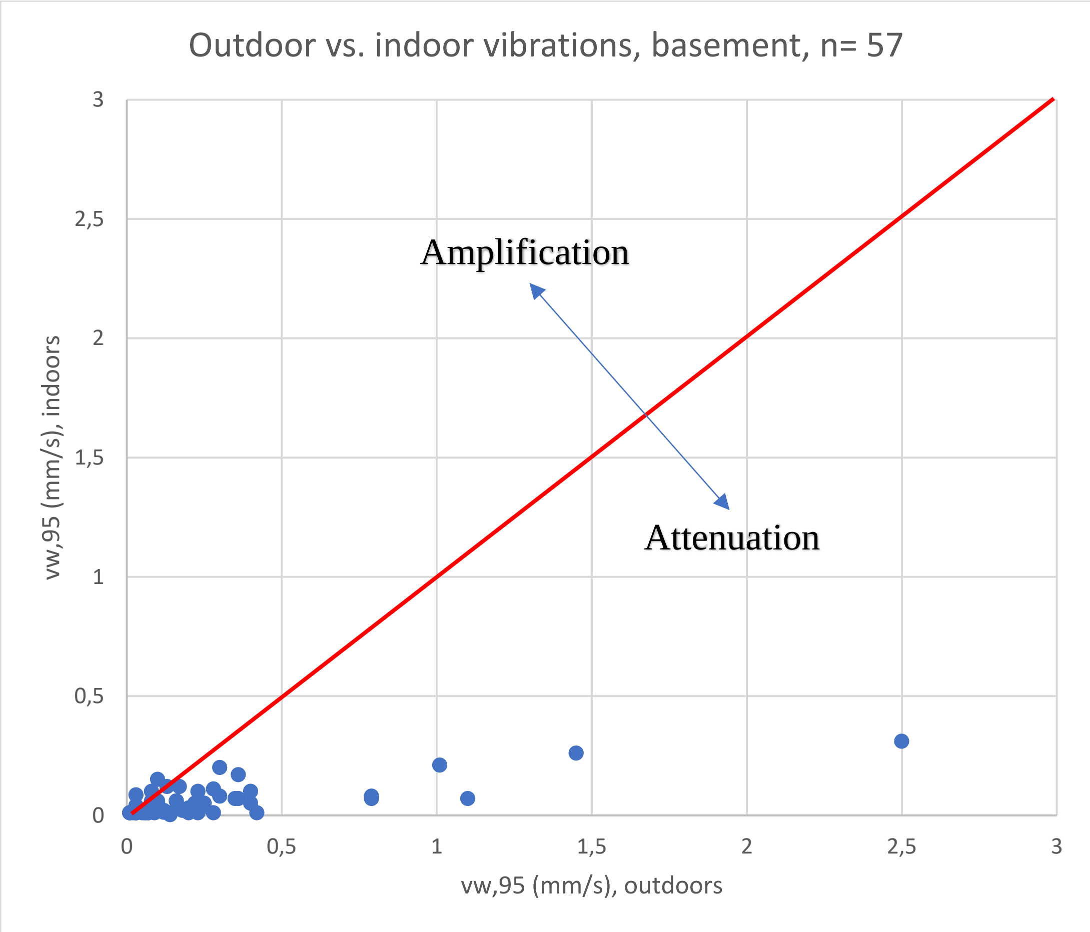

Figure 1, outdoor vs. indoor vibrations in basements, 57 cases

The correlation between outdoor and indoor vibrations in different directions is unclear in basements as shown in table 2. The indoor vibration level on basements is usually lower than the outdoor level, and it has been lower in all the cases where the vibration level is above v_{w95} = 0,15 mm/s.

Table 2 – correlation between outdoor vibration and vibration on basement floor

	x on basement	y on basement	z on basement
x on ground	0.6194396	0.7925603	0.7302024
y on ground	0.6083342	0.7783370	0.7228024
z on ground	0.6051977	0.7217160	0.6997887

3.3 Outdoor vs. indoor vibrations, ground floor

Ground floor is defined as the floor which has the level that is closest to the ground on the side of the house facing the track. Figure 2 shows the magnitude of weighted vibrations outdoors plotted against weigthed vibrations on ground floor.

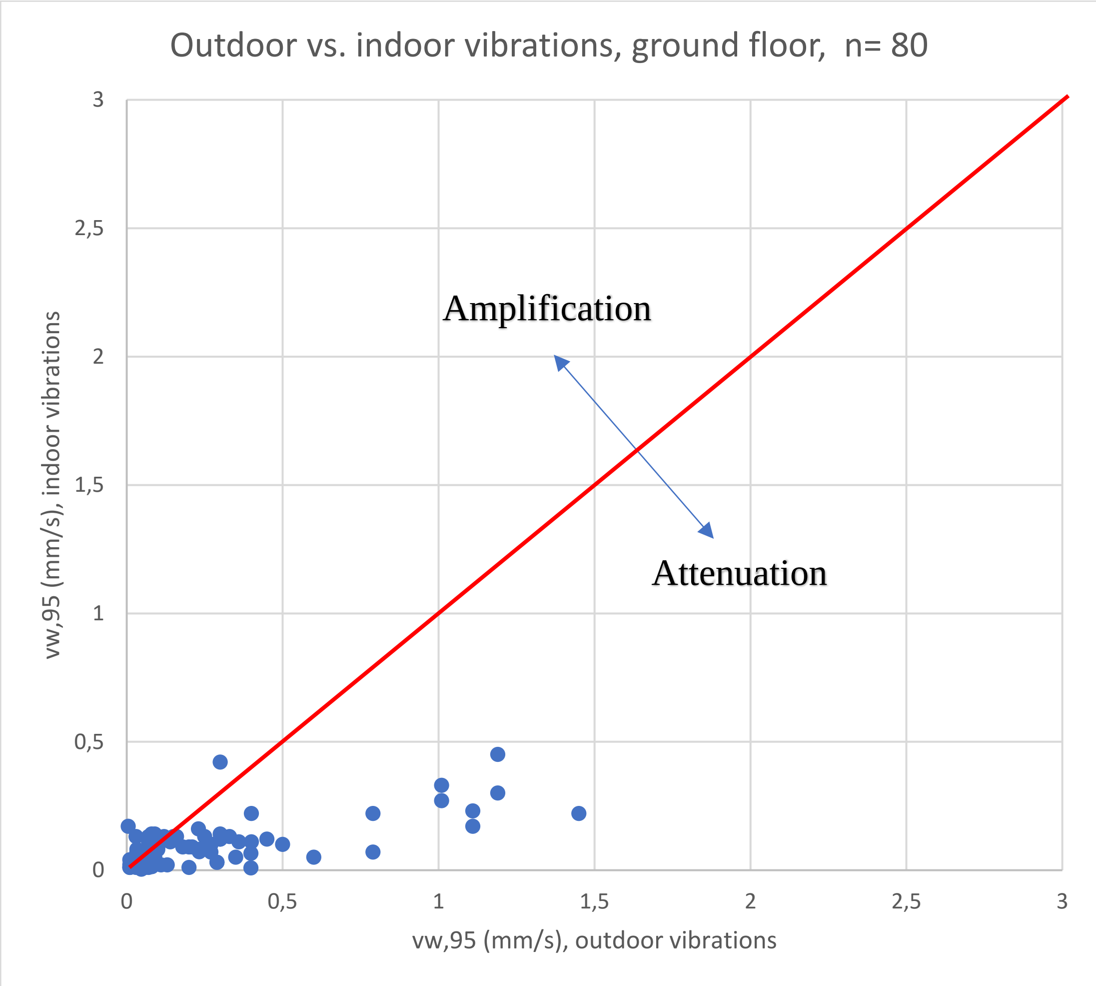

Figure 2, outdoor vs. indoor vibrations on ground floors

Table 3, correlation between outdoor vibration and vibration on ground floor

	x on ground floor	y on ground floor	z on ground floor
x on ground	0.5235226	0.5327929	0.6157803
y on ground	0.6194315	0.6421457	0.6570688
z on ground	0.6158081	0.6149453	0.6925445

The correlation between outdoor and indoor vibrations on ground floor. The correlation is weaker than in the basement. Only one critical case of amplification has been noted from outdoor vibrations to indoor vibrations.

3.4 Outdoor vs. indoor vibrations, first floor

Figure 3 shows the magnitude of outdoor vibrations plotted against magnitude of indoor vibrations on first floor.

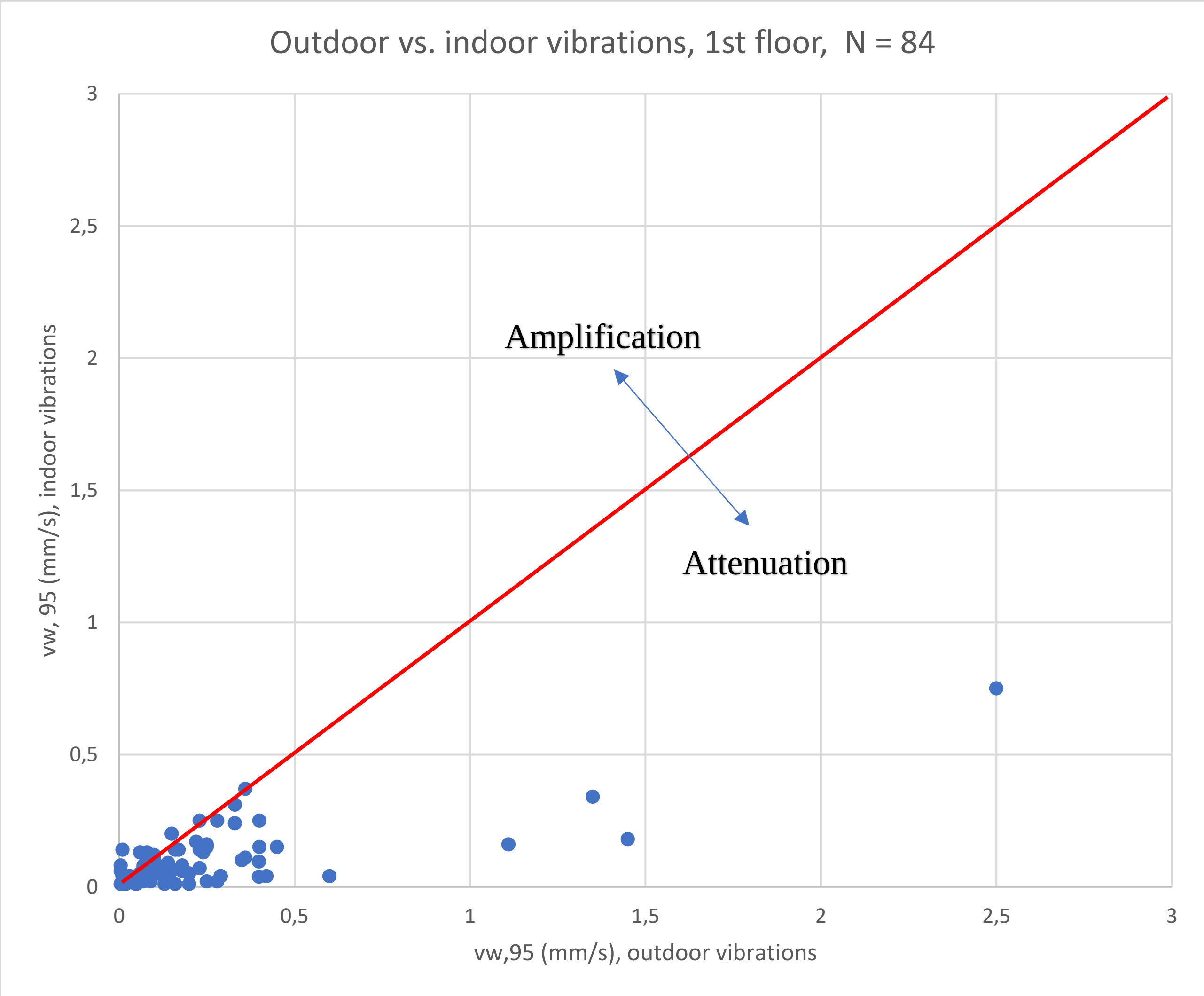

Figure 3, outdoor vibrations vs. vibrations on first floor

Table 4, correlation between outdoor vibration and vibration on first floor

	x on first floor	y on first floor	z on first floor
x on ground	0.4923813	0.4972882	0.7524553
y on ground	0.4500468	0.4519585	0.7112918
z on ground	0.5442518	0.5421559	0.7391754

On first floor the vibration levels tend to be higher in the z direction. No cases of significant amplification from outdoor vibrations to first floor vibrations have been seen. Vibrations on first floor tend to be vertical.

4 Discussion

So far only measurements of weighted vibration levels from Oslo's metro have been presented. The results are different from what should be expected from railways. It cannot be recommended to port the results from metro trains with a maximum speed of 70 km/h to mainline railways. It is quite likely that heavier trains travelling at higher speeds will excite vibrations in a very different way than the metro does.

The houses where the measurements have been made are mostly small detached houses or rowhouses with a brick or concrete structure below ground and a wooden structure above ground. They are different in details, but in general the measurements have been made in houses with a lightweight wooden structure. The ground conditions are varied, but not known in detail.

The spectra have been measured for each transducer and each passing train, but only a limited analysis has been performed for one case [4]. A few controls have been made of outdoor spectra, and in all the three controlled cases the highest vibration velocity came in the same 1/3-octave band.

5 Further work

It would be very interesting to have a similar series of measurements with other vibration sources or different house structures. It would also be interesting to perform spectrum analysis of transfer functions. The first attempts do not appear to give results that can be interpreted in a simple way.

6 Acknowledgements

Thanks are primarily due to Sporveien, the company that runs the metros and trams of Oslo, and that has commissioned the measurements that constitute the basis of the paper. Further my heartfelt thanks are in place to many of my colleagues at Brekke & Strand, in particular Arild Brekke, who has explained many things about the transfer of vibrations, Atle Stensland, our project manager, Teresa Fernández Espejo and Tore Fodnes Killengreen who have helped out with the field work and preliminary analysis of measurement data.

References

[1] NS 8176. *Vibration and shock. Measurement of vibration in buildings from landbased transport and guidance to evaluation of its effect on human beings.*

[2] S. Olafsen, *Indoor noise from urban railbound transport*. Ph. D. thesis, Lund, 2016

[3] A. Stensland, S. Olafsen, *Environmental noise and vibration monitoring of Oslo's metro lines*, Baltic Nordic Acoustical Meeting 2018, Reykjavik

[4] S.Olafsen, *Transfer functions of vibrations from metro trains to houses*, Baltic Nordic Acoustical Meeting 2014, Tallinn