Noise and Vibration Reducing Measures to the Souterrain Tramtunnel in The Hague Optimally Tuned to the Situation

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Noise and vibration nuisance in residential and office buildings near to traffic tunnels can be prevented by paying attention to vibration isolating and reducing measures at the tunnel and/or the building whilst in the design phase. A vibration prognosis, supported by local measurements, enables optimal tuning of noise and vibration reducing measures to the local situation. This article explains the evaluation criteria and elaborates upon the noise and vibration isolating measures applied to the Souterrain Tramtunnel in The Hague intended to prevent nuisance in the residential and office buildings near to the tunnel.

1. INTRODUCTION

Building in an urban environment along and above train, streetcar and subway lines or crowded roads is equivalent to building in a noise and vibration polluted environment. Vice versa, the construction of a tunnel in an urban area means an additional noise and vibration loading to the existing environment.

The noise load on the environment generated by road and rail traffic is mainly determined by the immediate noise radiation of the vehicle: the rolling sound of tires or wheels, the engine noise and with rail traffic the air flow of the air along the vehicle. This noise is passed through the air to the environment and causes (airborne) noise loading of the facades of nearby buildings. Depending on the noise reducing properties of the facade a certain noise level will develop in the rooms behind the facade.

With vehicles in tunnels the direct noise radiation through the air is blocked, the tunnel and soil enclose the source of the noise. Therefore at tunnels there is no noise pollution through airborne noise. With tunnels the noise load to the environment is determined by the structure borne noise, which is caused by the vibrations of the vehicle passing through the tunnel. As a result of this the structure of the tunnel and the surrounding soil starts to vibrate. The vibrations migrate through the ground and excite nearby buildings through their foundations. Depending on the strength and frequency of the vibrations these can be felt perceptibly by people. Moreover as a result of the vibrating floor, walls and ceiling in a room (low frequency) structure borne noise is radiated.

Often tunnels are constructed only a few meters away from or directly underneath the foundation of buildings. Therefore the perceptible vibrations and structure borne noise are higher than at roads on ground level, which are usually located at larger distances from buildings.

2. TRAFFIC VIBRATIONS

Traffic vibrations originate from the rolling of wheels and tires on the contact surface of the road and the rails, and from the elastic deformation of the contact surfaces under the load of the vehicle. Because of this, varying forces are working on the structure while the amplitude and frequency depend upon the roughness of the contact surfaces, the magnitude of the deformations of the contact surfaces, and the velocity of the vehicle. Furthermore the mass of the vehicle, the suspension and the unsprung mass of the wheels and axles, and also the mass and stiffness of the supporting structure are of significance. These parameters determine the vibration levels and dominant frequencies. As an example, with rail traffic the strongest vibrations occur at frequencies in the range of 20 to 100 Hz and with heavy road traffic between 5 and 20 Hz.

3. REFERENCE FRAMEWORK FOR PERCEPTIBLE VIBRATIONS

For the assessment of vibration nuisance in the Netherlands until today there exists no legislation. From 1993 onward the directive 2[1] "Hinder voor personen in gebouwen door trillingen" ("Nuisance for individuals by vibrations in buildings") published by the Dutch Stichting Bouwresearch has been used. By now there is sufficient jurisprudence to regard this directive as the commonly accepted assessment criterion.

According to this directive vibrations in the interval from 1 to 80 Hz are relevant. The vibration level[2] is measured continuously and for each interval of 30 seconds the highest level is determined. The assessment quantities for nuisance are: the highest vibration level V_{max} measured on the floor of a room and the vibration level during the extent of the assessment period (day, evening, night). The directive gives three target values (A_1, A_2 and A_3) for this, which depend on the function of a building, the nature of the vibration source and the assessment period for the vibrations. If the vibration level is lower than the target value no vibration nuisance is to be expected (see explanation in box1)

For residential buildings near to traffic tunnels the target values for the nightly period are normative. In this case the highest allowable vibration level V_{max} is equal to the target value A_2 of 0.20. At this maximum vibration level per vehicle passage nuisance is prevented if V_{per} is lower than the target value A_3 of 0.05. This means a limitation of the number of vehicles passing to seven per hour (see box 1). For tunnels with high traffic intensity this limitation is too strict and is aimed at a vibration level V_{max} of 0.10. In this case the level A_1 is met and no vibration nuisance is expected. For office buildings the highest allowable vibration level is determined the same way at a V_{max} of 0.15 (A_1 for office buildings).

In case the target values for nuisance are met, the target values for damage to buildings are met implicitly. It follows from the SBR-directive A "Schade aan bouwwerken door trillingen" ("Vibration induced damage to buildings") that at least a vibration

[1] In 1993 the "Stichting Bouwresearch" (SBR) has published three directives concerning vibrations, the SBR directives 1, 2 and 3. In August 2002 those directives were revised and replaced by respectively the SBR directives A, B and C. In this the target values are unchanged but for the value of A_2 in the B directive, which is slightly increased.

[2] The vibration level is expressed in the advancing effective value of the weighted vibration velocity in mm/s. The advancing effective value is measured using an exponential filter and a time constant of 125 ms. This corresponds to the position "F" for fast on the equipment used for example in noise measurements.

Box 1. SBR-guideline 2 explained

SBR-guideline B, "Nuisance by persons through vibrations"
Target values for maximum acceptable vibration amplitude resulting from rail traffic to prevent nuisance by perceptible vibrations (new situations, a new building and/or a new traffic line).

Function of the building	Day- and evening period			Night period		
	07:00-19:00 hr 19:00-23:00 hr			23:00-07:00 hr		
	A1	**A2**	**A3**	**A1**	**A2**	**A3**
Residential and health care	0,10	0,40	0,05	0,10	0,20	0,05
Education, office and meetings	0,15	0,60	0,07	0,15	0,60	0,07

The vibration amplitude, expressed in V_{max} and Vper, is regarded acceptable if:

$V_{max} < A_1$ or if $V_{max} < A_2$ and $V_{per} < A_3$

V_{max} is the largest occurring vibration amplitude in the relevant evaluation period.

V_{per} gives the vibration load over the extent of the evaluation period. At this the time span with a vibration amplitude in excess of 0, 10 is determining for the level of V_{per}.

$$V_{per} = \sqrt{\left(\frac{k}{N} \times \frac{1}{n} \times \sum_{i=1}^{i=n} v^2_{eff,max,30,i}\right)}$$

with:
- V_{per} — Vibration load over the relevant evaluation period
- K — Time span of the vibration in the relevant evaluation period, the number of 30 second intervals
- N — Time span of the evaluation period, the number of 30 second intervals; day period $N = 1440$; evening period $N = 480$; night period $N = 960$
- n — Time span of the vibration measurement, the number of 30 second intervals
- $V_{eff,max,30,i}$ — Maximum vibration amplitude per 30 second interval, insofar $V_{eff,max,30,i} \geq$ 0, 10

Remark: If it is assumed that each vehicle passage lasts less than 30 seconds and the vibration amplitude for each passage is equal to the target value A_2, then the maximum permissible number of vehicle passages per evaluation period can be calculated, in such a way that V_{per} will stay just within the target value A3. For a residential building, for the night period, a target value of $A_2 = 0{,}20$ and $A_3 = 0{,}05$ is valid. To determine the maximum number of vehicle passages, the formula is filled in as follows: $V_{eff,max,30,i}$ = A2 = 0,20; $n = 1$; $N = 960$; V_{per} = A3 = 0,05. From this k is calculated, in this case k = 60. This means a maximum of 60 vehicle passing during the nightly period of 8 hours, or an intensity of maximally 7 vehicles per hour. Starting from the vibration level $V_{eff,max,30,i}$ = 0,20, it follows for the day- and evening period that the permissible intensity again is 7 vehicles per hour. If on the contrary is started from the target values for the day and evening period, a vibration level of $V_{eff,max,30,i} = A_2 =$ 0,40 and $V_{per} = A_3 =$ 0,05, then it follows that the permissible intensity in the day- and evening period is only 1 vehicle passage per hour.

velocity of 2 mm/s (peak) is allowed. This limit value is a factor 10 to 14 above the target values for nuisance. In some cases it is necessary to assess also the possible disturbance by vibrations caused by machinery and/or processes. The SBR-directive C "Storing aan apparatuur door trillingen" ("Malfunction of machinery by vibrations") gives a guideline for this.

4. REFERENCING FRAMEWORK FOR STRUCTURE BORNE NOISE

As a guideline the "Bouwbesluit" is used. In this for a residential building, for noise caused by road- and rail traffic, the characteristic noise reduction of the facade is tuned in such a way that that the noise level in the building will not exceed 35 dB(A) daytime value. This means that the equivalent noise level in a characteristic residential room will not exceed 35 dB(A) in the daylight period, 30 dB(A) in the evening period and 25 dB(A) in the night period. For office buildings the limit values are 40 dB(A).

Those requirements are valid for the equivalent noise level for the assessment period and do not yet put a limit to the maximum noise level while a vehicle passes. The legislation regarding road- and rail traffic does not take this into account. To prevent noise nuisance during the passing of a vehicle a maximum noise level is utilised of 10 dB above the equivalent noise level[3]. Using the night period as determining period the maximum noise level during the passing of a vehicle follows: 35 dB(A) for residential buildings and 50 dB(A) for office buildings.

5. REFERENCING FRAMEWORK FOR LOW FREQUENCY NOISE

Regarding the relatively strong vibrations that are generated by rail traffic at low frequencies, often low

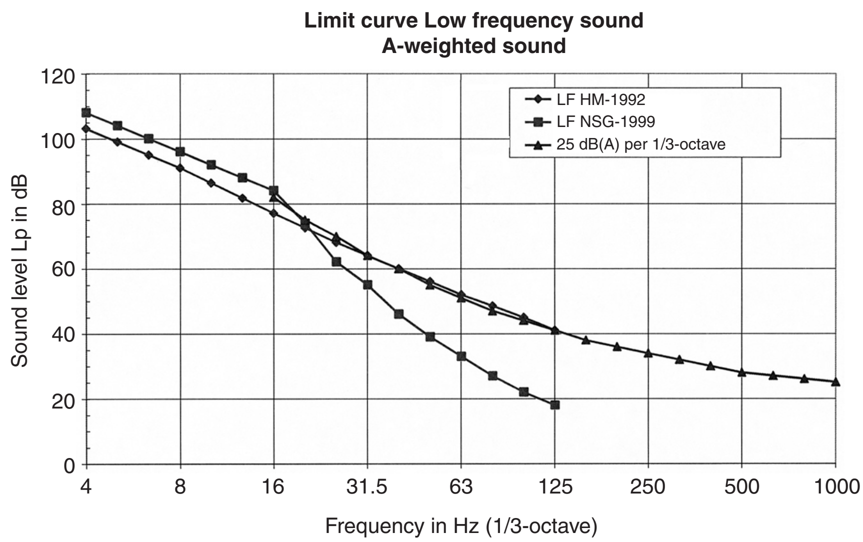


Figure 1. Limit curves for low frequency noise. Noise levels exceeding the limit curve lead to nuisance through low frequency noise. The NSG limit curve evaluates the noise levels at frequencies above 20 Hz to be unacceptable at lower levels than the HM limit curve, or the Bouwbesluit with 25 dB(A) in the corresponding 1/3-oktave band.

[3] In the "Handreiking industrielawaai en vergunningverlening", Dutch Ministry of VROM, 1998, a preferred value for the peak levels is mentioned as maximally 10 dB higher than the equivalent noise level.

[4] Samsom: Handboek voor milieubeheer, part III: Lawaaibeheersing, Februari 1992

frequency structure borne noise is present. In this case high noise levels occur at frequencies below 125 HZ. For low frequency structure borne noise no legal referencing framework is available.

Experience has taught that, in order to prevent low frequency structure borne noise by passing vehicles, the limit curve according to the “Handboek voor Milieubeheer”[4] can be used. At noise levels exceeding this HM-limit curve, nuisance through low frequency noise is encountered. This limit curve aligns well to the limit value of 25 dB(A) equivalent for residential buildings, when it is assumed that the noise level of 25 dB(A) is fully determined by the concerned 1/3 octave band.

In April 1999 the Nederlandse Stichting Geluidshinder (NSG, Dutch Association Noise Nuisance) formulated a guideline for continuous low frequency noise. The NSG-limit curve is partly below and partly above the HM-limit curve. The NSG guideline however assumes continuous low frequency noise and does not take into account the short period character of the noise, as with a passing vehicle.

6. VIBRATIONS AND RADIATED STRUCTURE NOISE

The structure borne noise radiated by a vibrating wall, floor or ceiling for a room can be calculated with the formula from Cremer and Heckl. Based upon this equation the structure borne noise resulting by a passing vehicle can be calculated, starting from the vibration loading on the structure, see box 2.

7. SOUTERRAIN TRAMTUNNEL

The Souterrain Tramtunnel in The Hague has a length of about 1200 meters and is part of the streetcar line from the Central Station to the city centre. The tunnel for much of the route follows the existing street plan: Muzen flyover, Kalvermarkt, Grote Marktstraat en Prinsengracht. The deep walls of the tunnel are located a short distance from the foundations of existing or planned shopping, office and residential buildings. In some locations the distance is less than 2 meters, at one point the tunnel passes below existing buildings.

The roof of the tunnel is located just below street level, the floor of the tunnel is approximately 12 meter lower with two storeys in between. On the tunnel floor two streetcar tracks are planned in which two stations are incorporated: Spui and Grote Markt. On the intermediate levels a parking lot is planned.

Setbacks during the construction of the tunnel have leaded to a number of adjustments. As a result of this, the available space for vibration reducing measures is in parts of the tunnel decreased rather drastically.

To prevent nuisance by vibrations and structure borne noise in the buildings near to the tunnel a vibration investigation was started. The aim of the investigation is to determine vibration isolation to the tracks, within the still available space, optimally tuned to the local situation. In this way the nuisance by vibrations and (low frequency) structure borne noise can be prevented, or at least reduced to a minimum.

From the first inventory of the buildings along the tunnel path the most critical situations for noise and vibrations were selected. Subsequently at a number of critical locations measurements were done, where the vibration transmission was determined between the tunnel floor and the building next to the tunnel. At these measurement locations the tunnel floor was excited with a force pulse, of which the amplitude and frequency content were measured (see figure 3a). Simultaneously with the force pulse the amplitude and frequency content of the vibration response was measured, on the

WHOSE PROBLEM?

From a patchwork of laws and a confusing chain of enforcement to few pressing reasons to focus on the issue, reducing noise pollution is an uphill battle in the state of Maryland, USA. In state government alone, half a dozen different agencies deal with noise, said George Harman, who heads the Maryland Department of the Environment’s two-man noise control program. On top of that, some city and county governments have their own laws on the books. For example, the Department of Natural Resources handles noisy boats. But local or state police show up at a raucous party and Animal Control officers handle a house with an obnoxious barking dog. The state Department of Labor, Licensing and Regulation makes sure workplace noise doesn’t hurt employees. But MDE steps in during a noise dispute between a business and nearby homeowners. And even when there are laws, are they always enforceable in practical terms, and if so, does the particular agency have sufficient trained personnel, does it really have the will … ?

GETTING THE BIRD

City Hall, Portland, Maine, is being made home by pigeons in unusually large numbers this year. So the city has bought a $500 solar powered machine that blares out electronic shrieks, intended to scare off the pigeons. Choosing the solar machine was, city officials say, essentially a cost and environmental issue. Unfortunately, it appears not to work.

tunnel floor as well as on the floors and walls of the building next to the tunnel. From the measurement the vibration transmission [mms^{-1}/N] as a function of frequency was determined.

A representative measurement result for two different locations is shown in figure 3b. It concerns a building at 2 meter distance from the deep wall and a building where the

Box 2. Vibrations and radiated structure borne noise

Vibrations and radiated structure borne noise

The radiated noise level by a vibrating wall, floor or ceiling can be calculated using the formulae of Cremer and Heckl

$$Lp = Lv + 10.\log(\sigma) - 10.\log\left(\frac{A}{4.S}\right) - 34dB$$

with: Lp Noise level in the room, dB(ref. 20 μPa)

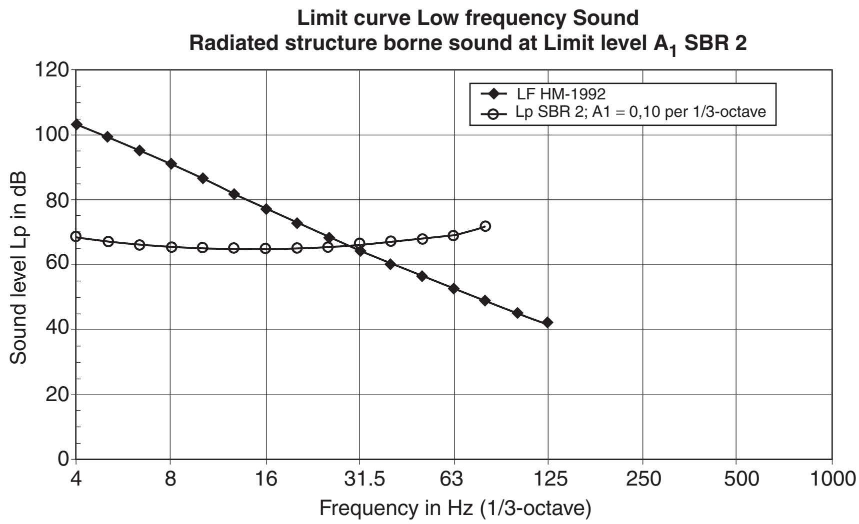
Lv Velocity level vibrating surface, dB(ref. 1 nm/s)

σ Degree of radiation, the efficiency with which noise is radiated

A Noise absorption in the room, m^2OW

S Surface area of the radiating surface, m^2

Remark: If for Lv the SBR limit curve A_1 = 0,10 is used, then the radiated structure borne noise by the floor can be compared to the limit curve for low frequency noise, see the graph below. From the graph it follows that for vibration frequencies below about 31.5 Hz 1/3-octave nuisance through perceptible vibrations is to be expected earlier than through low frequency structure borne noise. Above this frequency nuisance through low frequency structure borne noise is to be expected earlier.



Graph: *A noise level in excess of the HM-limit curve gives nuisance through low frequency noise. The SBR limit curve represents the radiated structure borne noise if the vibration level of the floor just complies with the limit value A_1 for nuisance through perceptible vibrations. In this case it follows that for frequencies above the 31.5 Hz 1/3 octave band vibrations in the floor do not lead to nuisance through perceptible vibrations, but nuisance through radiated low frequency structure borne noise is to be expected.*

Figure 2. *Deep walls of the tunnel are located very close to buildings.*

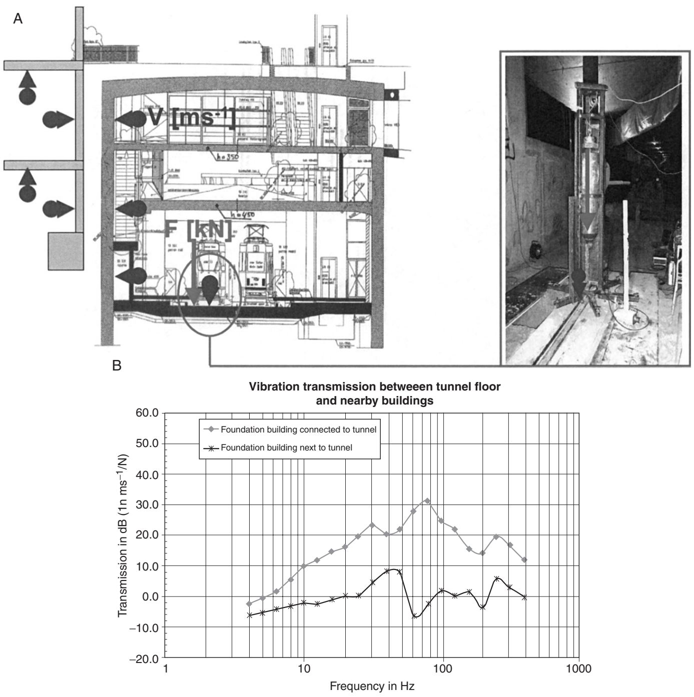


Figure 3. *(a) Vibration transmission measurement between the tunnel floor and the buildings next to the tunnel using a tuned impact hammer of 10 kg up to 250 kg. (b) Measured vibration transmission between tunnel and normative buildings. Vibration transmission as a function of the frequency [ms^{-1}/kN]; induced vibration velocity [ms^{-1}] divided by the excitation force [kN] causing the vibration.*

foundation is connected physically to the deep walls of the tunnel structure. For the last-mentioned building a clearly much stronger vibration transmission is found.

The vibration level in the adjacent building is predicted by multiplying the measured vibration transmission (figure 3b) by the measured force spectrum [N] with which the passing streetcar excites the railway track. From this, vibration level and vibration spectrum in the building are derived. Based upon the predicted vibration spectrum in the building the nuisance by perceptible vibrations and radiated (low frequency) structure borne noise is determined.

A first prognosis for the most critical building (figure 4) shows that without vibration reducing measures to the tracks, in case the rail is directly mounted to the tunnel floor, the vibration level at 99 dB stays just below the target value of 0.10 or 100 dB. The A-weighted structure borne noise level during a streetcar passage is then 54 dB(A) and hence much higher than the limit value of 35 dB(A). Furthermore the limit curve for low frequency structure noise is exceeded by about 25 dB. To prevent nuisance vibration reducing measures are necessary, especially to reduce the structure noise above 31.5 Hz.

VIBRATION REDUCING MEASURES

To reduce the vibration levels an Embedded Rail System (ERS), an Improved Embedded Rail System (IERS) and a floating concrete slab (FS) were investigated. The ERS requires a relatively modest construction height and in principle can be applied over the whole length of the tunnel. The attainable vibration isolation is limited to vibration frequencies above about 100 Hz. For the IERS the vibration isolation is improved for frequencies above 50 Hz. The FS is capable of a much higher level of vibration isolation, starting from frequencies around 16 Hz. The FS however has the disadvantage that it needs a relatively large construction height and therefore can be applied only to a part of the tunnel. The vibration reduction improvement is given in figure 5.

EMBEDDED RAIL SYSTEM (ERS)

With the ERS the rail bar is placed in a groove in the concrete of the tunnel floor. In addition to that under the length of the rail bar a running layer of an elastic material is applied. The remaining volume between rail bar and groove walls is then largely filled with an elastic material. The elasticity of the

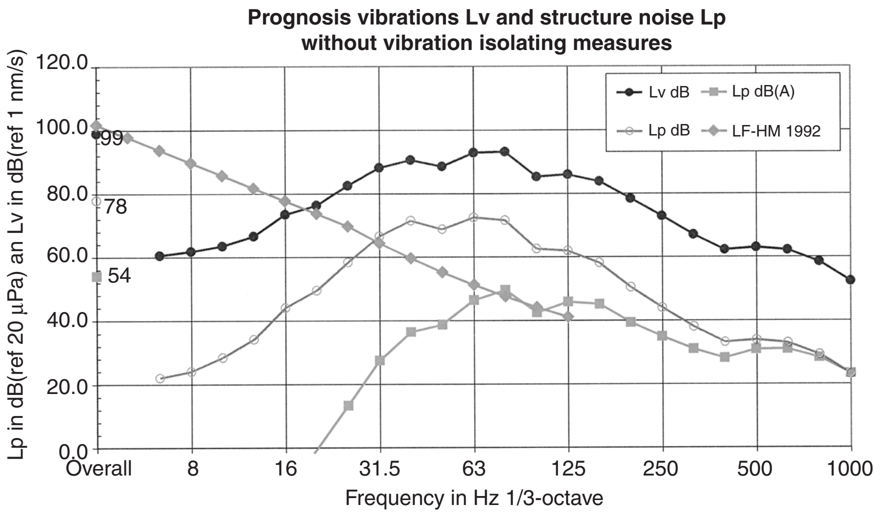


Figure 4. Prognosis Noise and vibration levels at a passing streetcar for the most critical building, without measures to the tracks.

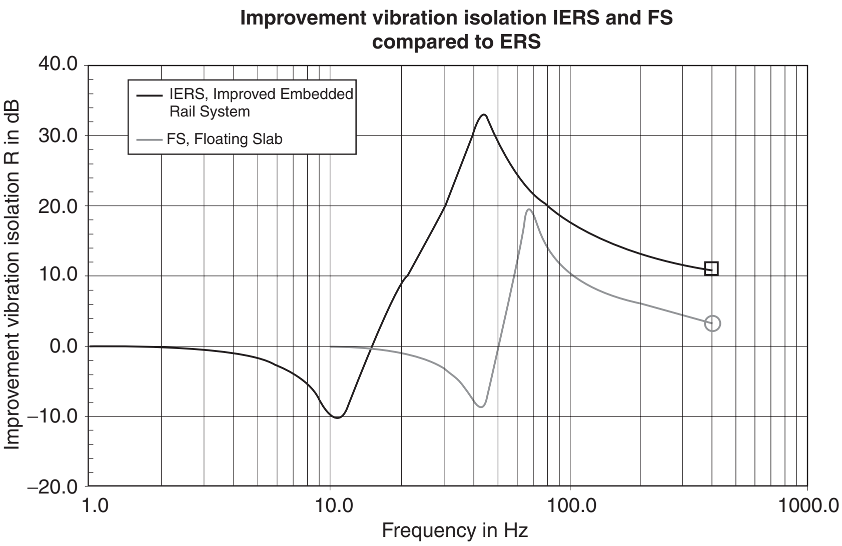


Figure 5. Increase of vibration isolation IERS □ and FS ○ compared to ERS.

runner and the material determine the sagging of the rail bar under the load of a passing wheel bogey. In this way the rail bar and bogey form a mass – spring system of which the natural frequency is around 70 Hz. The natural frequency is determined mainly by the elasticity below the rail bar and mass of the bogey. For vibration frequencies well above the natural frequency of the ERS a vibration isolation is realised, for the lower frequencies a vibration amplification will occur.

Measurements to an existing track with ERS and also to a test rig in the tunnel have shown that the vibration isolation of the ERS is not sufficient to prevent nuisance through structure borne noise for the complete tunnel length. Because of that an improved version of the ERS was developed using a different and thicker runner below the rail bar (IERS). The stability and lifetime of the track remains guaranteed, despite the higher elasticity of the embedding of the rail bar.

With these adjustments the natural frequency of the IERS is reduced to around 45 Hz. Compared to the ERS the vibration isolation for frequencies above 50 Hz is improved by at least 5 dB, with a maximum of 10 to 20 dB for frequencies between 60 and 100 Hz (figure 5).

The vibration isolation of the IERS is, for a major part of the tunnel length, sufficient to prevent nuisance through perceptible vibrations and low frequency noise. However, at the most critical location the system results in an amplification of the noise and vibration level. At this location, where there is sufficient space available in the tunnel for vibration reducing measures, the FS is applied.

FLOATING SLAB (FS)

In case of the FS the rail bars are mounted directly to a concrete slab with a thickness of about 500mm. Between the concrete slab and the tunnel floor an elastic layer is applied which creates a mass – elastic system. As a result of the large mass of the concrete slab in this system a relatively low natural frequency of around 11 Hz can be obtained. This results in vibration isolation from vibration frequencies above about 16 Hz. Compared to the existing ERS the vibration isolation for frequencies from 20 Hz increased by at least 10 dB, with a maximum improvement of 20 to 30 dB at frequencies between 30 and 70 Hz (figure 5).

Using this FS at the most critical location in the tunnel, nuisance through perceptible vibration and low frequency noise is prevented (figure 6). The

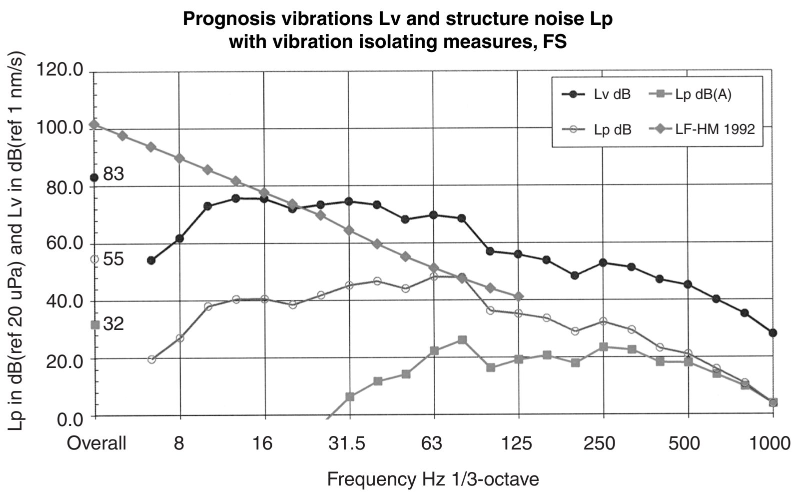


Figure 6. Prognosis noise and vibration levels at a passing streetcar at most critical building, with tracks on Floating concrete Slab.

vibration level of a passing streetcar is reduced to 83 dB, well below the target value of 100 dB. The noise level at a passing streetcar is then 32 dB(A) and is well below the limit value of 35 dB(A), while the limit curve for low frequency noise is not exceeded.

CONCLUSION

In the vibration investigation for the Souterrain Tramtunnel in The Hague newly developed vibration isolating measures are optimally tuned to the local situation, based on advanced measuring and calculation techniques. As a result of this, nuisances through perceptible vibrations and low frequency structure borne noise in buildings near to the tunnel are prevented.

HOUSEPROUD? BEWARE!

Early morning and late night vacuuming is now outlawed under a new noise crackdown by Brimbank City Council, Victoria, Australia. If a noise complaint is received for vacuuming between 10pm and 7am on weekdays and 10pm and 9am on weekends, cleaners can be given a $205 on-the-spot fine. This rises to a $1000 court fine if it is not paid, and subsequent violations attract fines of up to $2000. Under the new law, the noise must be able to be heard in a room of another house – regardless of whether the window or door is open. Jim Smith, a public health consultant to the Municipal Association of Victoria, said the on-the-spot fine would be welcomed by complainants who don't want to wait before laws were enforced. "There are increasing levels of complaints because people don't want anything to do with their neighbours," he said. "And with high-density housing, the level of tolerance is diminishing."

COST OF OFFICE NOICE

Office noise – computers, phones, faxes, printers – costs British business an estimated £139 billion a year – or so research commissioned by Brother claims. It suggests that office workers can lose up to two hour each working day – the equivalent of 45 days a year – because of broken concentration, which it costs at £4,903 per employee each year. The survey of 1,800 home and office workers found that almost two-thirds (64%) of office workers reckoned they were interrupted up to 20 times per day and 18% complained that they were distracted more than 20 times, adding up to a staggering two to four hours each day.