Statistical analysis of railway noise: trackside monitoring of individual trains

E. Verheijen[a], M.S. Roovers[b], J.W. van den Brink[b]
[a]*dBvision, Vondellaan 104, 3521 GH Utrecht, The Netherlands*
Tel: +31 6 29076165 , Fax: +31 30 281 9844, E-mail: edwin.verheijen@dBvision.nl
[b]*ProRail, Postbus 2212, 3500 GE Utrecht, The Netherlands*

Abstract

For the purpose of monitoring the progress of the Dutch Noise Innovation Programme, the infrastructure management organisation ProRail has installed 5 noise monitoring stations on the railway network in the Netherlands. These monitoring stations record noise spectra and rail vibration spectra of train pass-bys. A weather station is integrated to allow the exclusion of data recorded during windy and rainy periods. As the stations are also capable of identifying vehicles by tag reading, a unique possibility is created for statistical analysis of railway noise and monitoring individual trains and vehicles.

A statistical data analysis programme has been conducted by Railway Noise Knowledge Centre of ProRail. In this programme, the performance of a number of silent pilot trains has been monitored. These passenger and freight trains have been equipped with LL braking blocks, which are expected to keep the wheel running surface smooth. The monitoring stations provide information on the long-term performance in terms of noise reduction.

It occurs that the noise emission of some train types is not constant through the year: seasonal effects are observed and an attempt to clarify this is given.

The analysis programme also involves an evaluation of the source parameters of the Dutch railway noise prediction method (RMR). These source parameters, which relate to the type of rolling stock, have been derived and established in the mid 1990s. Fortunately, it is found that the average noise emission of most train types is still close to the RMR values. For some train types, however, a significant lower noise emission value is measured currently. This will probably lead to an adjustment of the source parameters.

Furthermore, the usability of the noise monitoring in noise-based railway access charging is considered. For this specific purpose, the reliability and accuracy of individual pass-by measurements is assessed. Special attention is paid to the measurement uncertainty caused by local track properties (effects of rail roughness and track construction), which, of course, should be eliminated before assigning a fine to noisy trains.

Finally, the statistical relation between noise emission, rail vibrations, rail roughness and wheel quality is investigated.

1. Introduction

1.1. Noise monitoring and source recognition

Noise monitoring is common practice in the assessment of industrial and aircraft noise sources. For these applications, the stand-alone equipment comprises of an outdoor microphone and weather sensors connected to a computer for recording and processing. Spurios noise events (related to other sources than the ones under investigation) are eliminated automatically or manually during post-processing. A large range of reasonably priced equipment for these applications is avialable.

Noise monitoring is a much more complex task if the noise events and sources need to be classified into (sub)types. For road vehicle identification, (visual) license plate recognition can serve that goal. In the case of railway vehicles, the principle of axle patterns recognition is often used to classify the type of rolling stock [1, 2]. The principle is based on the fact that the distance between successive axles of a train is typical for each type of rolling stock. This method is suitable for classification purposes, but is inadequate for the monitoring goals set by the Noise Innovation Programme.

1.2. Noise Innovation Programme and project goals

Within the railway part of the national Noise Innovation Programme [3], retrofit solutions are applied to trains with cast-iron braking blocks. In order to study the long-time noise effects caused by the new braking blocks, monitoring stations are developed that are capable of identifying the pilot trains and measuring their respective noise levels. Apart from this task, the stations are also used to check the average and spread of the noise emission of regular trains and compare these to the values that are incorporated in the Dutch railway noise prediction method (RMR, [4]). The third goal for monitoring is to assess the usability of the stations for noise-based access charging. Finally, the relationship between noise emission and rail vibrations is studied, as well as the extent to which wheel defects cause higher noise emission. The project is led by ProRail, the infrastructure management organisation.

The design properties of the monitoring stations have been described elsewhere [5], and will only briefly be repeated here. The main part of this article is reserved for measurement results and the analysis results. In conclusion, recommendations are given for improvement the systems and for further research.

2. Monitoring station

2.1. Design goals and specifications

Five noise monitoring stations have been designed and built in conformity with Procedure A of the *Reken en Meetvoorschrift Geluidhinder*, a national regulation for calculation and measurement of railway noise[1]. This basically means that the monitoring stations meet the requirements for the measurement environment, track condition, microphone position, rail roughness and weather conditions.

Each station (see Figure 1) consist of a stand-alone computer, two microphones and accelerometers (one per track), a weather station and a data transmission modem (GSM). For train recognition, the monitoring stations make use of Radio Frequency Identification (RFID) tags. All passenger coaches, multiple units and locomotives of the main Dutch train operator NS are provided with RFID tags. These tags are part of the existing systems "Gotcha" for wheel quality maintenance and "Quo Vadis" for weigh-in-motion [6], to which the monitoring station is connected.

[1] This regulation has become part of the European interim computation method for railway noise [4].

2.2. Measurement parameters

The following data are generated automatically after each train pass-by:

1. ID of monitoring station
2. Date and time of the pass-by
3. Noise: A-weighted sound exposure level (SEL) + octave spectrum 63 Hz – 8 kHz
4. Vibration Exposure Level of the rail (analogous to SEL, vertical vibrations of rail foot) + octave spectrum 31,5 Hz – 8 kHz
5. Pass-by time from buffer to buffer
6. Noise quality control (a value proportional to the reliability of the noise analysis result)
7. Track quality control (a value proportional to the reliability of the vibration analysis result)
8. Name of the train operator
9. Number of vehicles
10. Speed at the front and speed at the tail
11. Track number
12. Tag numbers
13. Rolling stock type
14. Noise category number (according to the national classification system)
15. Wind direction and speed, precipitation, air temperature

Besides noise and vibration data per pass-by, each monitoring system produces status information on a daily and on a monthly basis to facilitate maintenance and control. The measured data and status information is transmitted each night via a GSM connection to a central database (about 100 kB per day per station). The original noise and vibration signals (1 to 10 MB per pass-by) are erased from the station, unless the corresponding tag numbers are found in a local look-up table of pre-selected trains. This table can be changed remotely by the system administator.

The central database can be accessed through an internet application. The web application consists of analysis tools which show the results in downloadable graphs and tables [7].

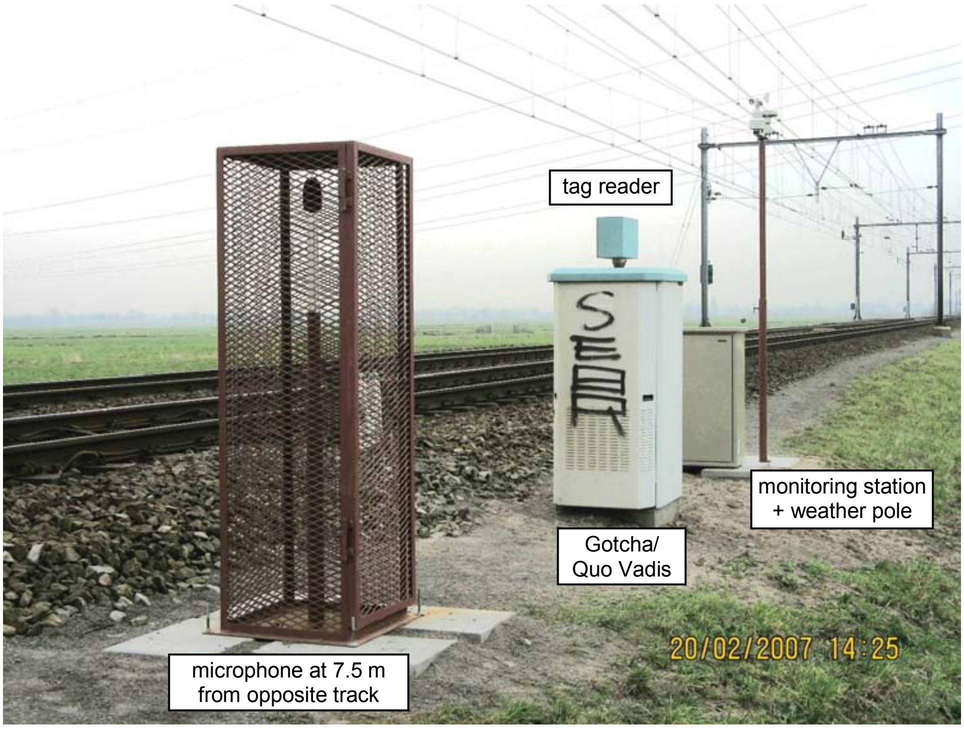

Fig. 1. Noise monitoring station along the railway track (line Weesp – Almere).

2.3. Quality control

In order to acquire reliable data from unmanned stations, extensive quality checking is required, because

- rail roughness may vary in time;
- trains may cross simultaneously on both tracks;
- microphone base levels may drift;
- weather conditions may be beyond ISO 3095 requirements;
- trains may accelerate or brake during pass-by.

These possible errors could be avoided of by automated rail vibration measurements, pass-by time checking, and daily microphones calibration, respectively. Unvalid data due to bad weather conditions and non-constant speed are excluded manually before further analysis.

The rail roughness is measured manually once a year. Depending on the analysis task, the measured noise data are compensated for rail roughness differences.

2.3. Measurement period and locations

The measurement stations have been developed in 2004, and installed and tested over 2005. Full operation has started in April 2006. The first operation and evaluation period will end in December 2007, as then the Noise Innovation Programme is concluded. ProRail intends to continue noise monitoring from 2008 as a means to check the actual noise emission from trains.

The monitoring stations are located on the main lines in the railway network, see Figure 2. One of the five stations is a non-permanent station. It has been equipped with only one microphone and accelerometer, which makes it more easy to move it to another location. The track system is Dutch standard ballasted track: 54E1 rail profiles on concrete sleepers (NS90) with stiff pads (FC9).

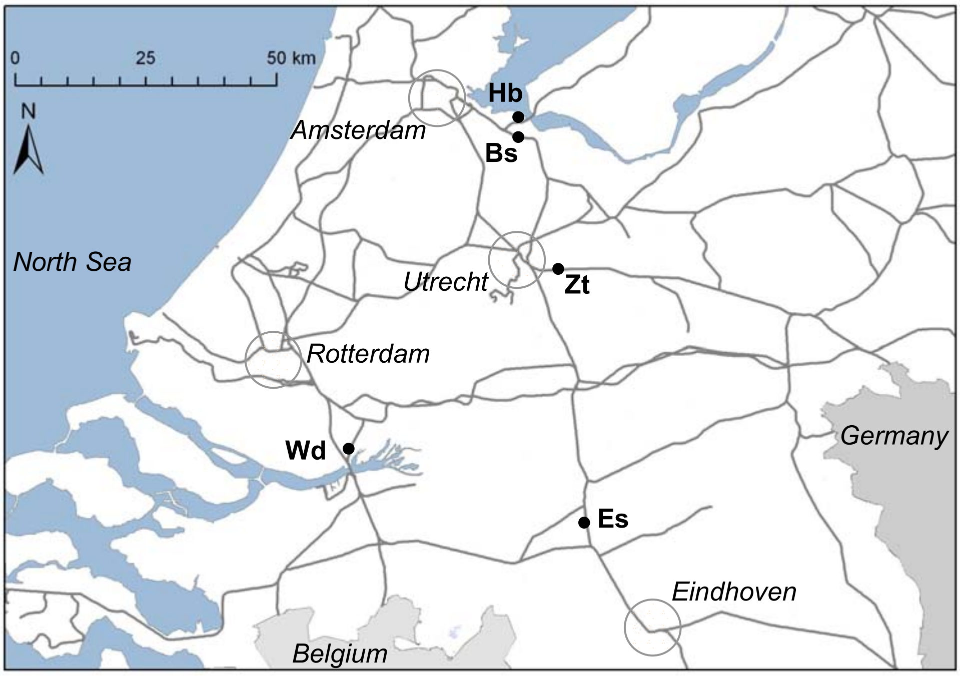

Fig. 2. Railway network and positions of noise monitoring stations (Wd, Es, Bs, Zt, Hb).

2.4. System performance

The performance of the stations is monitored by means of key performance indicators. The most meaningful one, *availability*, is defined as the percentage of days without high level status warnings. Also other performance indicators are defined, concerning data quality, data connection and train recognition. These indicators are computed by the central database application on a weekly basis.

The average value of the performance indicator *availability* is shown in Figure 3. While a performance of over 95% was aimed at, the realised performance is clearly much lower. This is mainly caused by problems related to the accelerometers, which frustrate the triggering of the measurements (e.g. deterioration of mechanical contact). Practically all of the stations seem to suffer from this every now and then. Unfortunately, the repair times for accelerometer failures are long due to safety regulations, as track closure is required. This also means that no train pass-bys are available for testing, which affects the success rate. Other failures, that occur incidentally, are related to instable hardware components like the modem, temperature control, weather station, back-up battery (UPS) and hard disk. In some cases, the repair of failures has been postponed or prioritised because of the needs of the analysis programme.

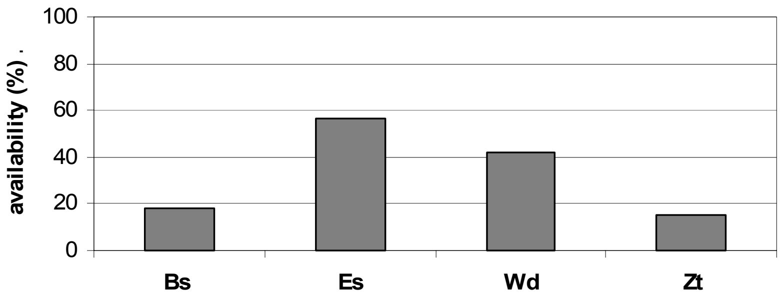

Fig. 3. Average system performance during the first operational year.

3. Monitoring trains

3.1. Introduction

Monitoring of trains can be carried out for an individual train (with a certain serial number) or for trains from one specific type. This section shows examples of both cases.

3.2. Trains with LL braking blocks

The braking system of type "ICR" passenger coaches consists of disc brakes with additional cast-iron braking blocks. Within the Noise Innovation Programme, the bogies of a small number of passenger coaches have been reprofiled and retrofitted with LL braking blocks. The coaches are kept together in fixed groups of three vehicles and are used in normal service trains that also contain coaches with cast-iron blocks. They run on several lines and will sometimes run on a line that is equipped with a monitoring station.

Figure 4 shows the development of the pass-by noise level of the middle coach of one of these groups, since the moment of reprofiling and retrofitting. Each circle represents one pass-by. The measurements are all taken from one track of station "Es". The rail roughness of that line lies between the ISO3095 limit and the TSI+ limit. The daily mileage of the coaches is approximately

1500 km. The graph shows a gradual increase of the noise emission during the first two months. The noise level stabilises after 2 months (approximately 40.000 km). At that point, it is still much below the original level for cast-iron blocks. This will be reported elsewhere [3].

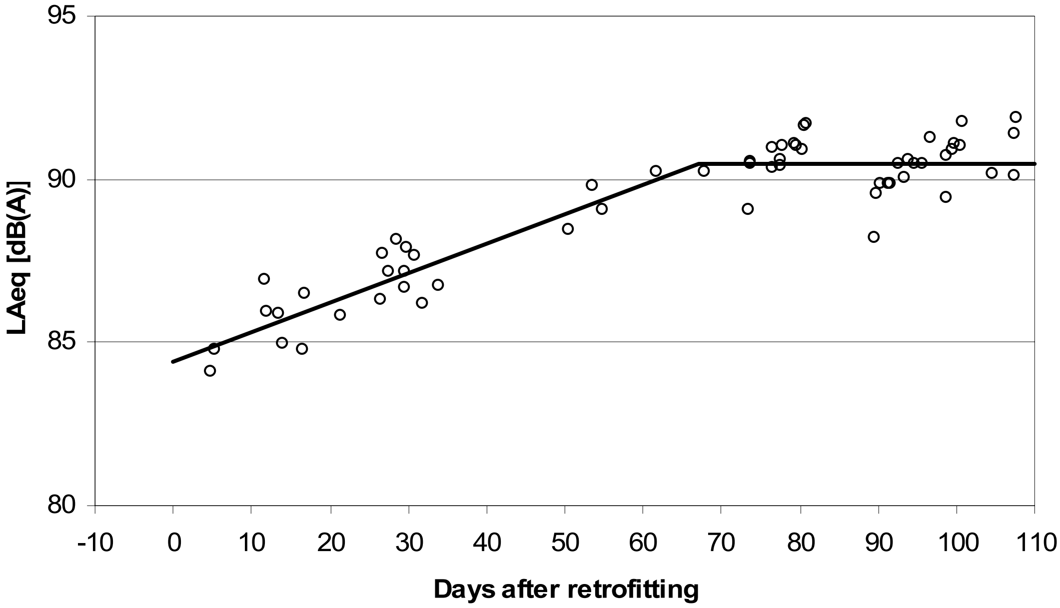

Fig. 4. Development of pass-by noise level after retrofitting and reprofiling.

Thanks to the monitoring stations, it is now known that with LL-blocks it takes much more time to obtain representative noise levels than, for instance, with cast-iron blocks. This information is important for type testing programmes and also for measurements that feed the prediction method.

3.3. Season effects

The monitoring stations have also yielded unexpected season effects for train type "IRM". This double-decker EMU with disc brakes is one of the most silent trains within NS rolling stock. By comparing the monthly average noise emission between April 2006 and March 2007 from different monitoring stations, it is found that IRM noise levels suddenly increase by 2,5 dB(A) in November 2006, see Figure 5. This increase is most probably related to wheel flats that originate from adhesion problems in autumn. This is supported by evidence from spectral analysis, showing the wide-band increase which is typical for impulsive sounds.

Though the observed increase is considerable, it must be remarked that there is no effect on the annual average noise emission level L_{den}, as the L_{den} is usually dominated by the noisiest trains that run on a line.

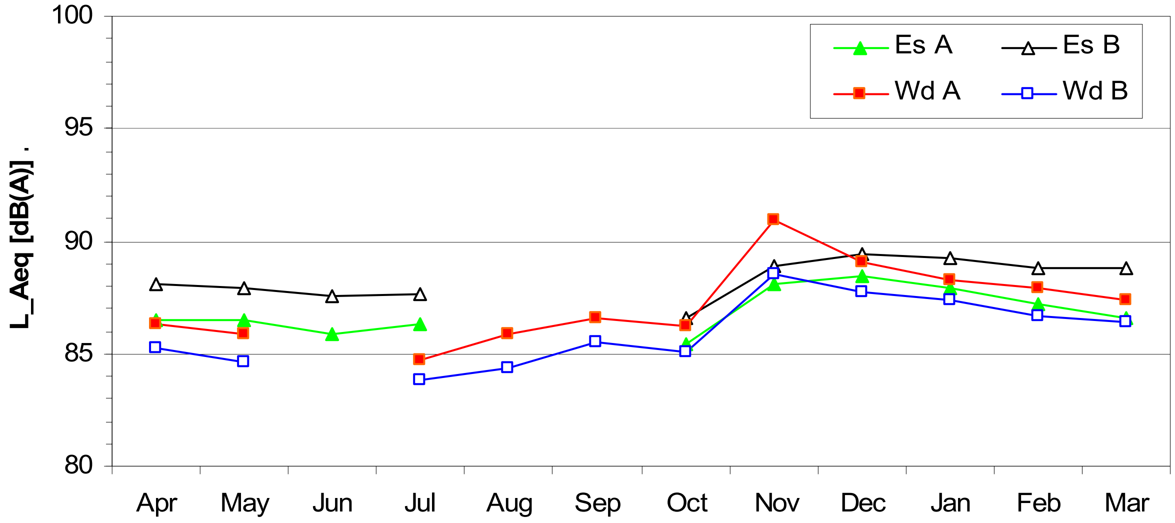

Fig. 5. Season effects in the monthly average noise level of IRM rolling stock.

4. Actual noise emission compared to noise prediction model

4.1. Train categories

At present, eleven categories of trains are distinguished in the Netherlands on the basis of their noise emission. Each category has a fixed set of source parameters for rolling noise and (if applicable) braking noise, traction noise and aerodynamic noise. The parameters were originally determined in the early 1980s and updated and extended in the mid 1990s [8]. Although there has been no particular reason to doubt the values of the parameters, it is considered that the noise monitoring stations offer a good possibility to check these parameters and to update them, if necessary. Under the Noise Abatement Act (*Wet geluidhinder*), an update of these parameters would affect the required strength and amount of noise reduction measures in future construction plans for houses and railways.

A dataset of 10.000 pass-bys has been analysed. Most of these are from the first half of May 2006 from three monitoring stations. The measured rolling noise of fifteen types of rolling stock out of six categories has been compared with the theoretical values.

4.2. Results

Fortunately, none of the examined trains have become noisier over the last decade. On the contrary, three types of trains turned out to be quieter than expected. Also, for two types of trains a steeper slope was found in the dependency between speed and noise emission. These trains are about 3 dB less noisy at a speed of 80 km/h, but still show good agreement at maximum speeds of the conventional network (130-140 km/h). An interesting novelty is that the high speed trains ICE and Thalys could be compared under normal operating conditions, albeit at “conventional” speeds (maximum 140 km/h).

Two examples of these phenomena are given in the next subsections. All measurements have been corrected for rail roughness in conformity with the prediction method (see reference [9], equation (1)).

4.2.1. Type IRM

The A-weighted equivalent noise level versus speed of 225 pass-bys of IRM trains is given in Figure 4. This train type is a double deck EMU with disc brakes, introduced in 1994. The measurements are taken at 7,5 m from the track. The respective monitoring stations and tracks for each measurement are given by different symbols. The least squares fit is also drawn, as well as the curve of category 8 from the prediction method.

The actual noise level lies 2 to 2,5 dB(A) below the legal noise level of this category. The category by itself is still valid for other types of trains, but it can be considered to create a new category for IRM trains. However, as the noise level at most locations along the railway network is (still) dominated by much noisier trains, the effect will be negligible for most lines.

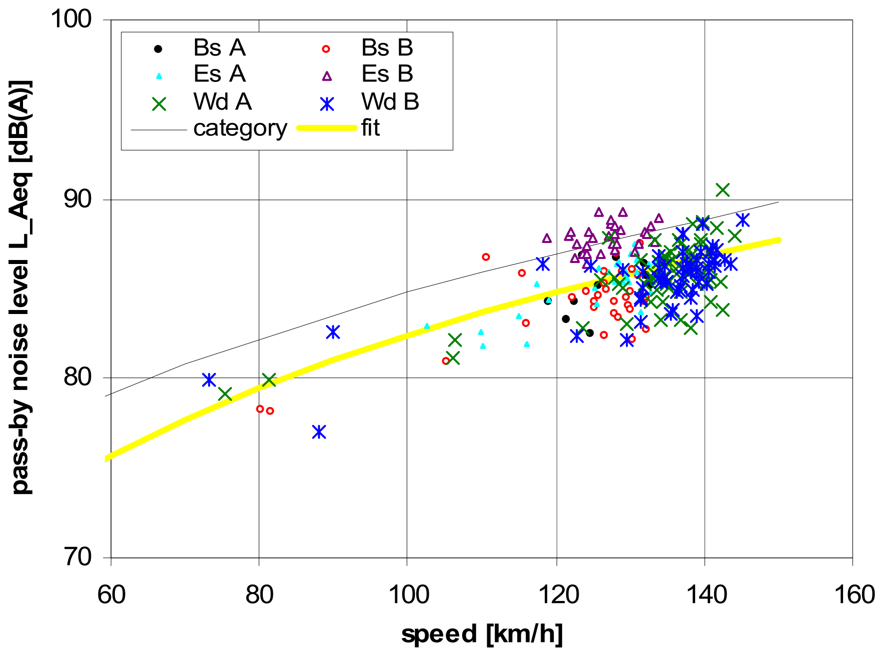

Fig. 4. A-weighted equivalent sound pressure level of IRM trains.

It is not clear why the noise emission of the IRM rolling stock has reduced by 2 dB over the past decade. The original measurements show that IRM had virtually the same noise levels as the other trains in its category, in 1995 [8]. Two later changes may, however, have affected its performance: enhancement of the wheel maintenance cycle via Gotcha [6] and an extension of the number of vehicles in one EMU.

4.2.2. High speed trains at conventional speeds

The noise levels of ICE (type 3M) and Thalys (types PBA and PBKA) are compared in Figure 6. The measurements originate from different monitorings stations, but have been corrected for differences in rail roughness. In the speed range to 140 km/h, both types of high speed train produce very similar results. Even the change of slope around 125 km/h can be observed for both trains.

It is interesting to note that the Thalys has a small theoretical advantage of 0,9 dB because it has less axles per meter than ICE: 26 axles per 200 m against 32 axles per 200 m for the ICE. Apparently, this advantage does not lead to a significant lower noise level on Dutch conventional track.

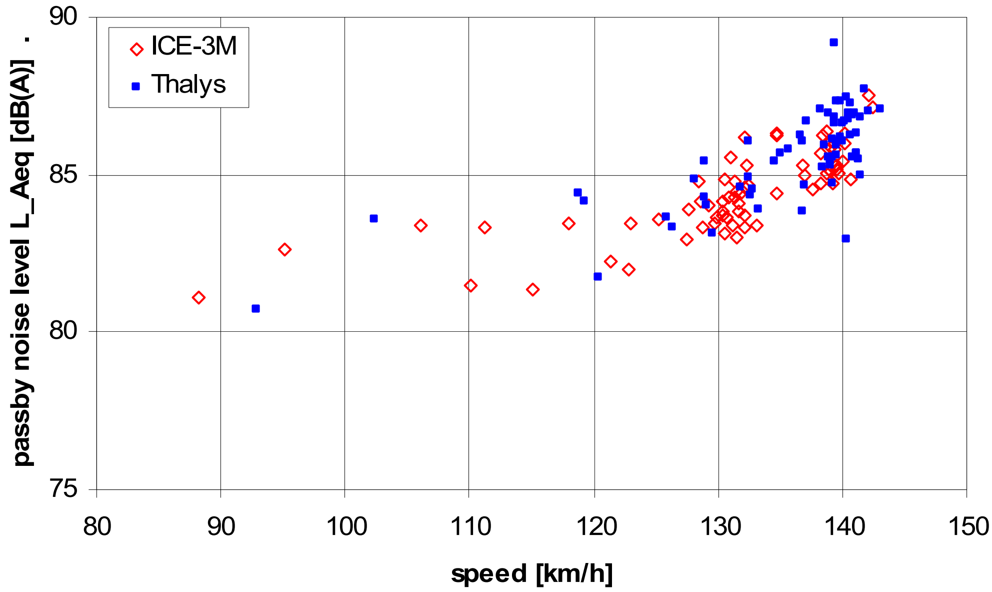

Fig. 6. A-weighted equivalent sound pressure level of high speed trains.

4.3. Conclusion

It has been shown that the monitoring stations can be used to assess the source parameters of the national noise prediction method. Monitoring stations can provide a larger statistical basis than manned measurements. Monitoring stations can also be used to determine the category of newly introduced rolling stock. They form an independant source of information and which is much more relevant to noise prediction than the type testing report that is delivered by the train operator (see also Section 3).

It is believed that significant changes of the actual noise emission will not occur on the time scale of one year. Therefore, the source parameters need only be checked once every two or three years.

5. Usability for noise-based track access charging

5.1. Track access charging

Railway operators have to pay for the use of the railway infrastructure for their services. ProRail aims at reflecting the weight of trains and the scarcity of rail capacity in the access charges. One of the environmental factors of scarcity is the noise emission. It is considered that noise-based access charges would stimulate the usage of silent rolling stock (new of retrofit). In principal, noise monitoring stations could play a role in the administration of noise emission, if sufficient stations are spread over the railway network. An important requirement is that the accuracy and reliability of the measurements must be without any doubt.

5.2. Sources of noise variation

It is relevant to distinguish between measurement errors and location dependent variations. Measurement errors are caused by malfunctioning of the system. Location dependent variations are found when noise measurements from the same train at different tracks or different lines are compared. They originate from differences in rail roughness, track geometry, pad stiffness, and ground impedance. The influence of these factors can be minimised by roughness correction, installation on straight tracks with standardised components, and measurement at a relatively short distance (7,5 m), respectively. The resulting spread for the monitoring stations is examined here. Only trains at a speed between 125 and 135 km/h are included in this analysis. A speed correction is applied. The spread is compared with the spread of manned measurements, reported in literature.

5.2.1. One train at the same track location

The standard deviation of multiple pass-by measurements of one train at the same track location is typically between 0,2 and 0,5 dB(A). This range is normally found during manned measurements of a test train running at the same speed. The standard deviation for the monitoring stations is on average 0,4 dB(A) in this situation, which is in good agreement with manned measurements.

5.2.2. One train at the different locations

The standard deviation of manned pass-by measurements of one train at the different locations lies between 1 and 1,5 dB(A) after correction for rail roughness. These figures are found for a block-braked passenger train at 30 different locations in the Netherlands [10]. A slightly higher spread of 2 dB(A) is found with the round robin test train of the METARAIL project, on different track structures in different countries [11]. Here, no rail roughness correction was applied, but the rails were reasonably smooth.

Between the noise monitoring stations, a standard deviation of 1,4 dB(A) is obtained. This value (corrected for rail roughness) is found by averaging the results of 22 disc-braked trains that each passed along all stations within a few months. In the case of block-braked trains, the average standard deviation appears to be less: 1,1 dB(A). Both values comply with the range for manned measurements.

5.2.3. Measurement errors

The main measurement errors of the monitoring stations are caused by faulty triggering. Generally, such errors can be recognised easily as the recorded pass-by time, train length and speed should be consistent. These three parameters are determined independently from each other, which leads to a high reliability. It is, however, possible that the wrong part of a noise record is cut, while it's length is still correct. The consistency check does not reveal such time shifts, which may lead to small underestimations of the noise emission. Underestimations, however, will generally not bother operators and are no serious thread for the system's reliablity for track access charging.

5.3. Conclusion

It is concluded that the performance of the noise monitoring stations is as accurate and reliable as manual noise measurements. However, the question if noise measurements are useful for track access charging, it depends on the method of charging. If the charge is related to the actual noise emission of a train, noise measurements are useful. A matter of concern is the poor up-time of the stations, shown in Figure 3. If the charge is related to the number of silent vehicles in a train, noise measurements are not sufficiently discriminating. This will be problematic for mixed freight trains, of which some vehicles may be retrofitted while others are not. In that case, tag numbers can be used to identify and count the number of bonus vehicles relative to malus vehicles.

6. Questions regarding noise emission, rail vibrations and wheel defects

Regarding the statistical relation between noise emission, rail vibrations and wheel quality, a few research questions have been formulated. Questions and answers, taken from reports [12] and [13] are summarised in this section.

Is it possible to monitor rail roughness indirectly by monitoring rail vibrations? Can rail vibrations be used then to correct noise emission levels for rail roughness variations?

The rail vibrations as measured by the monitoring stations are too unstable or too inaccurate to serve as indicator for rail roughness variations. In the long run, sudden jumps in the average vibration levels can be observed. These are probably related to changes of the mechanical connection of the accelerometer. The vibration levels measured by the monitoring stations vary much more from train to train than what can be expected from rail and wheel roughness.

Have rail vibration levels any predicting value for (absent) pass-by noise levels? This is interesting for trains that cross simultaneously on both tracks.

It is not possible to calculate a meaningful noise level from the vibration levels. The correlation value between noise level and vibration level across all types of trains is only 0,75. But even if only trains of one type are considered, it is still impossible to predict their noise level: some silent trains cause higher vibration levels than noisier trains.

Can high dynamic forces in the rail during a pass-by, which are associated with wheel defects, be related to high noise levels?

Dynamic forces are measured per axle by the Gotcha/Quo Vadis system. If the dynamic forces are extremely high and reproducible, they indicate wheel defects. It is found that some trains with a substantial of wheel defects have a higher than usual noise level. However, this appears not to be a general rule. Some trains that cause high dynamic forces have fairly normal noise levels.

7. Conclusions

The noise measurement stations have proved to be excellent tools to study railway noise emission. Especially, the train identification feature creates unique research possibilities. The monitoring stations allow for regular updates of source parameters for the noise prediction method and they provide reliable information about the performance of silent pilot trains.

It is recommended to reconsider the use of accelerometers for triggering and for rail vibration measurement. The benefit of measuring rail vibrations could not be proved, while the accelerometers are held responsible for poor availability (up-time) of the system. Other triggering devices can overcome this problem.

Acknowledgements

The Noise Innovation Programme (*Innovatieprogramma Geluid*) develops measures to tackle traffic noise at the source, to make Dutch railways and highways quieter. Rather than inventing new technologies, this programme uses available knowledge from earlier (European) research projects and prototypes from industrial research projects and puts them to practice. It attempts to speed up the long road from the prototyping phase to the actual implementation of source measures, which consists of both engineering and legal challenges. The programme includes the development and

data analysis of the noise measurment stations and is initiated and sponsored by the Ministries of Transport and Environmental Affairs.

References

[1] Automatic vehicle classification by axle pattern recognition is a widely used technique for the railways.
[2] Monitoring Eisenbahnlärm, Jahresbericht 2006, Bundesamt für Verkehr, (Robert Attinger)
[3] The Noise Innovation Programme website (also English) is www.innovatieprogrammageluid.nl
[4] Reken- en Meetvoorschrift Geluidhinder 2006, Bijlage IV en Technische Regeling, Ministerie van VROM. A translated earlier version is available at http://circa.europa.eu/Public/irc/env/noisedir/library
[5] J.W. van den Brink, Permanent Measurement Stations for Railway Noise, *Proceedings of Euronoise 2006,* Tampere, Finland, June 2006, paper 235.
[6] G. den Buurman, A. Zoeteman, A vital instrument in asset management, *European Railway Review* Issue 3 (2005) pp. 80-85.
[7] J. Lub, The Web Processing and Presentation of Railway Noise Monitoring Data, *Proceedings of Euronoise 2006,* Tampere, Finland, June 2006, paper 238.
[8] G. Janssen, "De geluidemissieformules van nieuw en bestaand spoorwegmaterieel voor de standaard rekenmethoden I en II; een voorstel op basis van metingen", NSTO report 9471096/9571114, Netherlands, 21 December 1995.
[9] E. Verheijen, A survey on roughness measurements, *Journal of Sound and Vibration* 293 Issue 3-5, p. 784-794. 2006. doi:10.1016/j.jsv.2005.08.047
[10] P. Dings, "Spoorstaafruwheid, spoorstaafdwarsprofiel en geluid", CTO report CTO/7/10448/0021, Netherlands, April 1994.
[11] M. Wirnsberger , M.G. Dittrich, J. Lub, G. Pollone, M. Kalivoda, P.v. Buchem, W. Hanreich, P. Fodiman, METARAIL Project – Final Report for Publication (D13), December 1999.
[12] E. Verheijen, "Relatie tussen geluidemissie, railtrillingen en ruwheid", dBvision-report PRO020-01-20, 20 March 2007.
[13] E. Verheijen, "Relatie tussen geluidemissie, wielkwaliteit en belading", dBvision-report PRO020-01-27, 22 May 2007.