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News and needs in outdoor noise prediction

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Abstract

"Empirical" models for predicting outdoor noise are being replaced by new models based on "physics" and with a wider field of application. This trend is supported by the increasing availability and speed of computers. The future will probably show a move towards numerical methods as a consequence of further increasing computer power. Attempts are being made to separate source and propagation in order to allow independent updating of source models and of propagation models.

1. Background

Prediction methods for environmental noise from roads, rail and air traffic and from industry have existed for decades. A recent survey made on behalf of the EU Commission by its Noise Policy Working Group No. 3 on Computation and Measurement concluded that none of the existing methods applied in the EU member states are completely adequate for future use as a common European standard. There is scope for significant improvement, even for the most advanced methods presently available.

The day, evening, night noise level L_{DEN} averaged over a reference year will be used in Europe as a metric for environmental noise impact on people. Therefore in prediction we shall have to deal with the combination of varying source noise emission and varying sound path attenuation. The variation can be caused by daily or seasonal variation in source operation (e.g. traffic intensity) and in weather conditions.

To simulate the noise levels occurring during a reference year, new investigations are needed on for example traffic noise source emission during warm and cold, wet and dry road surfaces. Likewise, weather statistics are needed for every location in Europe.

The nighttime noise exposure in Europe shall be described by $L_{\mathrm{Aeq,night}}$ that is one of the components of L_{DEN} and perhaps by supplementary metrics such as L_{AE} (SEL) or L_{AFmax} caused by single events. In case such single event noise metrics are introduced, their definition is crucial to the methods for prediction and measurement.

2. Terminology

This section is an attempt to define some basic concepts to prevent misunderstandings from occurring in discussions because people put different contents into the same word.

A *source model* is a combination of point sources representing a real noise source under specified operating conditions.

A *transmission model* is a set of algorithms describing the attenuation between a point source and a receiver point.

Source modelling is a process in which a combination of point sources is determined, each with a sound power level and directivity. When applied with appropriate sound propagation models agreement is obtained between measurement results collected near the source (emission measurement) and measurement results collected further away. Source modelling is for specialists, and advanced equipment like microphone arrays may be useful as a tool.

Emission measurement is measurement under standardised conditions of the noise from the source considered. Only one measurement distance should be specified and only one or a few microphone heights. Measurement results should be applicable for noise certification of vehicles and aircraft under prescribed operation conditions. Emission measurements should be cheap, and non-specialists without advanced measuring equipment should be able to perform such measurements.

An emission measurement result is characteristic of the actual (category of) source with its actual operating conditions. For example road surface and tire type, age and wear are all part of the *source operating conditions* as well as the speed, engine revolutions and throttle position. Vehicles change with time, and the reduction of power unit noise which has taken place along with a gradual tightening of the limits for vehicle noise emission has changed the "balance" between tire/road noise and power unit noise. Thus, source models will have to be kept up-to-date.

When a *database* is wanted, the data format must be defined, e.g. along the following lines eliminating as far as possible the influence of sound propagation between source and emission measurement position *a)* source position(s), *b)* frequency spectrum of sound power level, and *c)* directivity (spectrum). A source model is needed to translate the result of an emission measurement into source data in the above format. A noise emission database could consist of a frequency spectrum plus a "source model number" for each source category/ operating condition. The level of the source noise is adjusted using the prediction method so that there is agreement with the result of the emission measurement.

The *uncertainty* of a predicted noise level is an interval in which the *true value* lies. It is difficult to quantify the uncertainty of a calculated noise level because the true value is unknowable. In some cases an accurate calculation method can be used to obtain an estimate of the true value, or the average of a large number of accurate measurements can be used. In this way experience can be gathered allowing a characterization of the uncertainty associated with prediction. A measured noise level may deviate from the calculation result due to the influence of weather, variation in source operating conditions, background noise etc. during the measurement.

3. "Empirical" and "physical" models

Many empirical methods have been applied for outdoor noise prediction, from inter- and extrapolation of a few measurement results to "semi-empirical models" based on an understanding of the mechanisms involved, but choosing simple algorithms to cope with the lack of computational power.

Methods of the past have often been "dB(A)-methods" of varying sophistication. Basically the source sound power spectrum has to be known in order to derive reliable rules for the behaviour of overall noise levels. Such models are in wide use for aircraft, road and rail traffic noise, each with their characteristic frequency spectrum shape. In some cases corrections have been defined separately for various "classes" of spectrum shape.

In order for a sound propagation model to be generally valid, it must provide the attenuation in frequency bands. The Dutch ground effect model [1] is an example of an advanced "semi-empirical" model. This model has been the basis of a.o. the Nordic and the German model for predicting noise from industrial plants and for ISO 9613 [2]. Measurement results were available in literature, for example the classical measurements at Radlett and Hatfield in UK, or they were collected in extensive Dutch campaigns. The results were combined with an idea by Embleton et al. [3] to consider groups of ray paths as illustrated in Figure 1. Waves travelling along "neighbouring" rays were assumed coherent while contributions from waves travelling along widely separated paths were considered incoherent. A downwind octave band ground effect model was established which was for a long time the most advanced practical prediction model available.

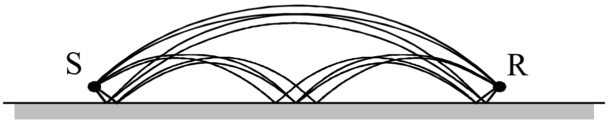


Figure 1: Curved propagation rays in a downward refracting atmosphere.

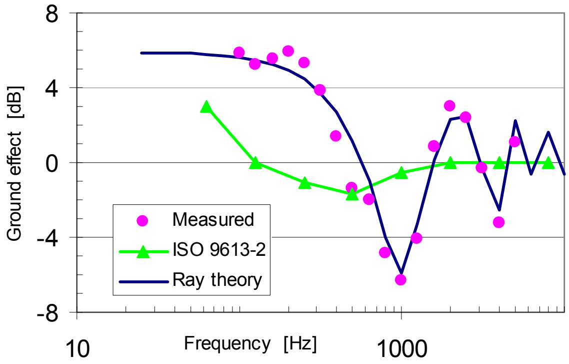


Figure 2: Ground effect. $h_S = 0.25$ m; $h_R = 0.75$ m; $d = 3.5$ m; $\sigma = 250$ kNsm^{-4}.

Figure 2 demonstrates the weakness of such a model. The model gives rather erroneous results when applied outside the range of measurement results it was based on. The figure shows the measured ground effect at a receiver 0.75 m above grass covered ground, 3.5 m from a source at a height of 0.25 m. This could be a source emission measurement. The figure at the same time shows nice agreement between measurement results and calculation using ray acoustic theory.

4. Reference models and engineering models

A new European project (HARMONOISE) on prediction methods for road and railway traffic and for industrial noise sources aims at a reference model, a "mother of all models" useful for special calculations and for calibrating simplified models. Such a reference model could consist of various parts each suited for its special purpose and with long computation time being less problematic than for models for practical prediction and noise mapping.

Among the candidate models in HARMONOISE are the Parabolic Equation (PE) model, Fast Field Program (FFP), Boundary Element Method (BEM), Meteo – BEM, Ray model with straight rays ("Neutral weather"), and Ray model with curved rays ("Refractive atmosphere").

With BEM complicated terrain shapes can be handled, but the weather influence cannot be included, and only limited distances can be dealt with. With PE the weather influence can be included and recently also the effect of irregular ground surfaces. Even the effects of strong sound speed gradients in the vicinity of noise barriers can be taken into account. FFP only works properly for flat ground although attempts are underway to change that. Meteo-BEM is a combination of BEM and PE/FFP. Computation times are too long for such models to be used for practical prediction and numerical and other problems may arise so expertise is required to run the calculations. Future development will hopefully change that.

The ray models are most appropriate for engineering calculations. The new Nordic model mentioned in the following section is such a model with straight rays and modifications to account for the ray curvature due to atmospheric refraction. Even the ray models with their relatively small computation times may prove too slow for mapping applications, and in that case simplified models may be needed.

The complexity of any propagation model to be applied in practical calculation should be at balance with the accuracy of the input data available for that calculation. The reference model, however, should be capable of handling non-linear, range-dependent sound speed profiles, e.g. near noise barriers, so it can be used to calibrate engineering or mapping models.

5. The new Nordic models

The new Nordic prediction methods consist of source modules for road and rail traffic and a sound propagation module. A source module for industrial noise sources will soon be available. The source modules contain data on point source strength and source positions while the propagation module contains algorithms for calculating one-third octave band attenuation during transmission from source to receiver. An overview can be found in [4].

The propagation model can be considered an engineering model. It is unique as a means of practical prediction in its foundation on physics, combining ray acoustic theory with diffraction theory. Ray acoustic theory deals with the frequency dependent interaction between sound waves travelling along different paths between source and receiver. When a ray is diffracted, the contribution to the sound field at the receiver is corrected for the diffraction.

5.1 Fresnel-zone

A Fresnel-zone approach has been essential in reaching at a generally valid and robust Nordic model. The method is based on a concept proposed by Hothersall and Harriott [5] for an approximate solution to predict sound propagation over flat terrain with varying surface types assuming the sound field at the receiver is determined by the surface conditions in a region around the reflection point. The method is described in [6] and [7].

The Fresnel-volume is an ellipsoid around the sound ray containing the essential part of the sound field. When the sound field is reflected from a plane surface the intersection between the surface and the Fresnel-ellipsoid defines the elliptically shaped Fresnel-zone, cf. Figure 3.

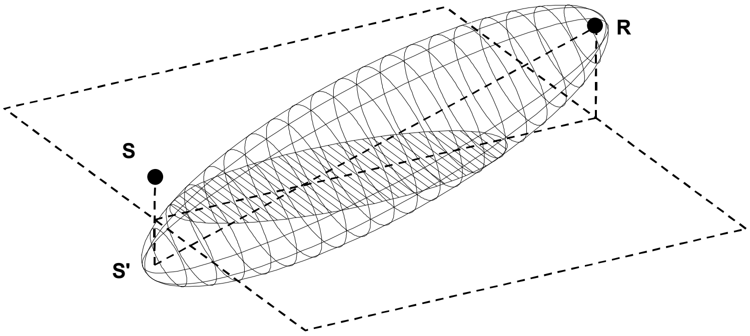


Figure 3: Illustration of the Fresnel-volume (“Nordic sound sausage”) and the Fresnel-zone on the ground.

Theoretical models are available for a variety of idealised situations with plane and horizontal homogeneous ground, vertical thin screens etc. In practical cases falling between such “idealised” situations the new Nordic model uses interpolation based on the Fresnel-zone as a means of weighting contributions from different basic models.

As an example Figure 4 illustrates how the effect of a terrain consisting of two different types of ground surface is dealt with. The ground effect is calculated for each type of ground surface, and the resulting ground effect is a weighted sum of the calculated effects. The weights are determined by the fraction of the Fresnel-zone occupied by the type of ground surface.

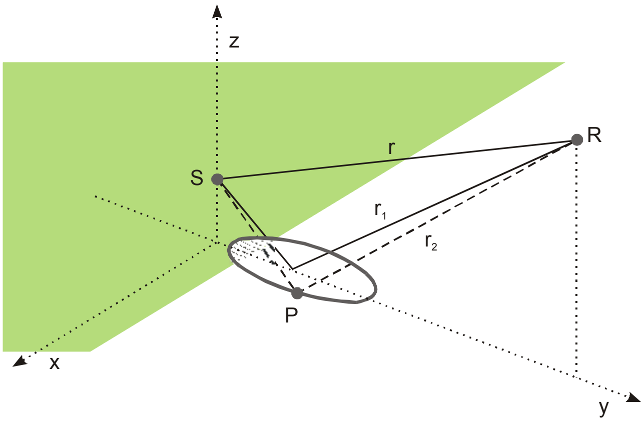


Figure 4: Fresnel-zone on a terrain with two types of ground surface.

Sound reflected from an obstacle such as a building facade is dealt with by introducing a new source at the image of the real source, mirrored by a plane containing the reflecting surface, Figure 5. The Fresnel-zone approach illustrated in Figure 5 ensures continuity when the reflection point moves from inside to outside the reflecting surface. No reflection would exist at the receiver according to the present Nordic prediction methods because the ray does not hit the building facade in Figure 5. In the new Nordic methods the effect of the part of the mirror marked "Active" in the figure is included, i.e. the part of the building facade inside the Fresnel zone.

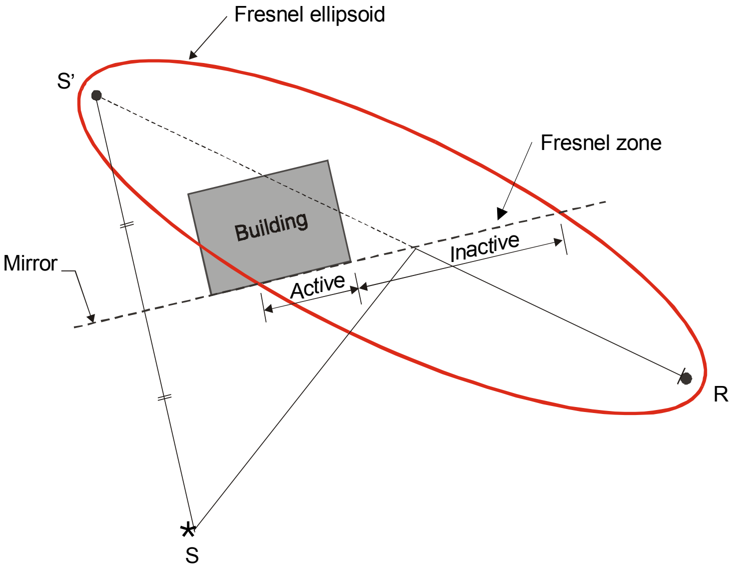


Figure 5: The reflected sound is proportional to the active part of the mirror.

5.2 Loss of Coherence

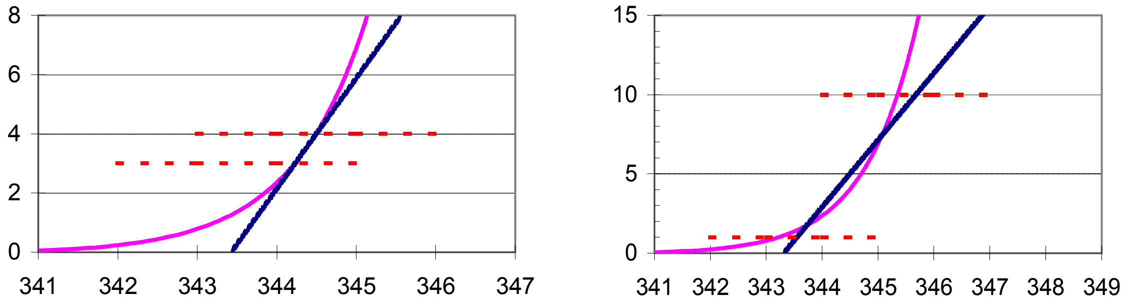
Ray acoustic theory yields more pronounced interference "dips" in calculated frequency spectra than is usually seen in measurements. In order to better model reality and in line with the ideas in [3] the new Nordic model has introduced various kinds of loss of coherence between the ray contributions [7]. The longer the distance and the higher the frequency, the less the coherence.

5.3 Weather

The effect of the weather on sound propagation is taken into account in the new Nordic model assuming the sound speed gradient to vary linearly with the height above the ground. This leads to circular rays, and the ray angles of incidence on surfaces and on diffracting edges are modified compared to the straight-line propagation.

In general sound speed profiles are not linear, more often they are logarithmic as illustrated in Figure 6. In order for the Nordic models to yield appropriate results, principles have been developed for representing the real profiles with equivalent linear profiles. The equivalent sound speed gradient is the average of the gradient between the source height h_S and the receiver height h_R, and the equivalent profile passes through the average sound speed between h_S and h_R [7].

The left part of Figure 6 illustrates that with a source and receiver height of 3 and 4 m, respectively, the linearised logarithmic profile is the tangent of the logarithmic profile at the midpoint between h_S and h_R. The right part of the figure shows the situation with a source at h_S = 1 m and a receiver at h_R = 10 m. Such a model can only deal with "uncomplicated" weather when the sound speed increases or decreases monotonically with increasing altitude and without significant jumps in the sound speed gradient.



h_S = 3 m; h_R = 4 m

h_S = 1 m; h_R = 10 m

Figure 6: The sound speed (on the abscissa, [m/s]) as a function of the height above the ground (on the ordinate, [m]). The logarithmic profiles illustrated by the curved lines are represented by the linear profiles shown.

In cases when many rays from a source reach the receiver after having been reflected from the ground, the new Nordic models add incoherent sound energy depending on the number of rays and on the ground absorption.

Also a model for the attenuation of sound propagating into a shadow zone is provided.

6. Sound source and transmission path

In existing methods the description of the acoustic energy radiated by the source is mainly based on the noise level measured at 7.5 to 25 m from the source. Such noise levels are influenced by the propagation path from source to observation point, and the measurement result contains elements of the source characteristics as well as elements of noise propagation. The propagation effects may be geometrical spreading or screening and scattering by objects between source and receiver as well as interference between direct sound and sound reflected from the ground.

Existing methods often base their validity on comparisons of the calculated nearby noise level with the measured level at more or less the same place. Such a comparison is rather useless if the source data used in the calculation are based on the same measurement. Further away from the source deviation between measurement result and calculation result may occur. It is at such larger distances that dwellings are found where the models are intended to produce their results.

De-coupling the modelling of the source from the modelling of the propagation is preferable although maybe not completely feasible, and the final proof of model validity would be that at several different distances and heights simultaneous measurements would all fit with results of calculation.

6.1 Source modelling – Directly measuring source strength

Arrays of microphones or a microphone mounted in the focal point of a parabolic acoustical reflector may be useful for qualitative measurements for locating sources during the process of creating a source model. Quantitative measurements are more difficult.

Figure 7 shows the angle with the system axis as a function of frequency for various degrees of side signal noise suppression, and Figure 8 shows the signal suppression as a function of the angle for a 1.8 m diameter parabola used by DELTA. An example of the resolution of a 9.5 m high array of microphones is given in Table 1. The spatial resolution is given for a measurement distance of 10 m.

Such systems are reasonably accurate at frequencies at 1 kHz or so and above. Larger systems are required to obtain a fine resolution at 100-200 Hz. The exact source height at low frequencies, however, is not very important for accurate prediction of the noise levels from road and rail vehicles. On the other hand the essential sound energy at high frequencies originates from around the road or rail surface, and a 0.5 m resolution or so is not sufficiently accurate to determine if the wheel or the rail is the source radiating the noise. So it may be questioned whether it is worth the effort to apply such systems. The present author is of the opinion that array or parabola measurements may be used to generate “qualified guesses” as to the quantitative vertical distribution (a source model) of the noise emission from extended sources such as a truck or a train. The final decision on the appropriate source model will have to be based on measurements made (simultaneously) at several distances and heights compared with calculation made with the source model and the propagation model.

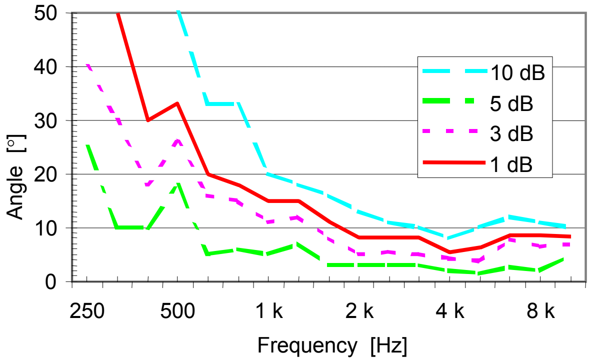


Figure 7: Angle [°] with parabola response lower than at 0° as given in legend.

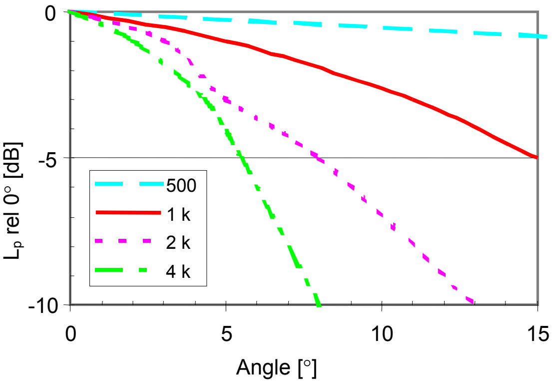


Figure 8: Parabola suppression [dB] of signal from the side.

Octave band centrefrequency [Hz]	Angular resolution [°]	Spatial resolution [m]
125	17	2,9
250	8	1,5
500	4	0,7
1000	2	0,4
2000	2	0,4

Table 1: Example of the resolution of a 9.5 m high acoustical antenna [8].

6.2 Emission measurement - Controlled sound propagation

As an example of vehicle noise emission measurement look at the proposed Nordic method [9]. Pass-by measurements shall be made at 7.5–15 m distance from the vehicle. Two microphones are used, one at 0.2 m and one at 4.0 m height. In the low microphone direct and reflected sound is in phase at low frequencies for every source height while in the high microphone there is minimum excess attenuation at high frequencies. The sound power level is determined by means of Eq. (1) assuming all sound to be radiated from the nearest wheel track.

$$L_W = L_E - 10\lg\sqrt{(d-\frac{w}{2})^2 + h_r^2} + 10\lg(v) - 10\lg(\Delta\alpha) + 10\lg\left[4\pi((d-\frac{w}{2})^2 + h_r^2)\right] - C_{ground} \qquad (1)$$

L_E = measured sound exposure level, d = horizontal distance from vehicle centre line [m], w = vehicle axle width [m], v = vehicle speed [m/s], h_r = microphone height [m], $\Delta\alpha$ = angle of circular sector covering the line of integration [radians].

For the microphone at 0.2 m height C_{ground} = 6 dB, and for the microphone at 4.0 m height the correction G_{ground} is shown in Figure 9. C_{ground} has been calculated using the Nordic vehicle source model and propagation model assuming that the impedance of the road surface is infinite and integrating over a range of $\underline{+}\,3d$.

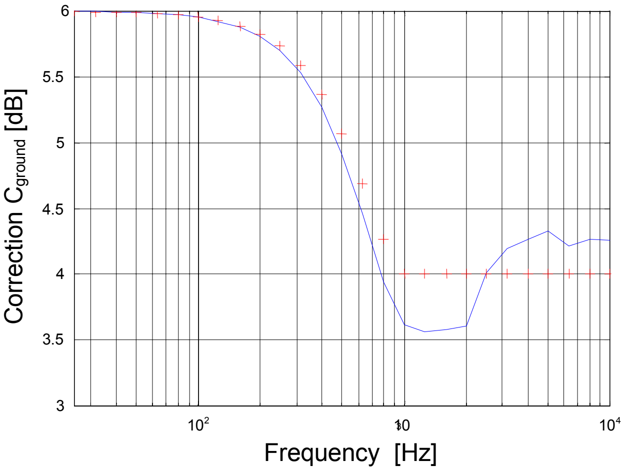


Figure 9: Correction C_{ground} in Eq. (1) for the 4 m position. Full line: calculated. Crosses: approximation [9].

The figure also shows an approximation recommended for road vehicles in the new Nordic models. The source sound power level is determined as the highest value obtained from the two receiver heights.

Applying the correction C_{ground} minimises the error due to interference effects caused by the measurement geometry. But still the sound propagation model is involved in determining the sound power level. The same applies to railway vehicles, and on ballast track the propagation conditions are rather complicated.

7. Source operating conditions

As an illustration of the task faced when designing a prediction method Figure 10 shows the noise emission from road vehicles as a function of speed under different driving conditions [10]. The numbers characterizing the noise emission are proportional to the sound power level of a point source representing the vehicle. Figure 10 discriminates between two kinds of vehicles: heavy and light, five kinds of driving pattern: constant speed, “pulsating” continuous, “pulsating” accelerating and “pulsating” decelerating traffic, and three kinds of road gradient: horizontal, uphill and downhill, all in all 30 combinations, some of which are identical in the figure. To the knowledge of the present author the emission data in Figure 10 are the most complex in any prediction method for road traffic noise.

These combinations are valid for one particular type of dry road surface. If one wants to predict the noise level at any other type of road surface, wet or dry, the “balance” between rolling noise and propulsion noise must be considered as a function of speed for each kind of road, road surface and driving condition. Simplifications will have to be made like the grouping of conditions in Figure 10.

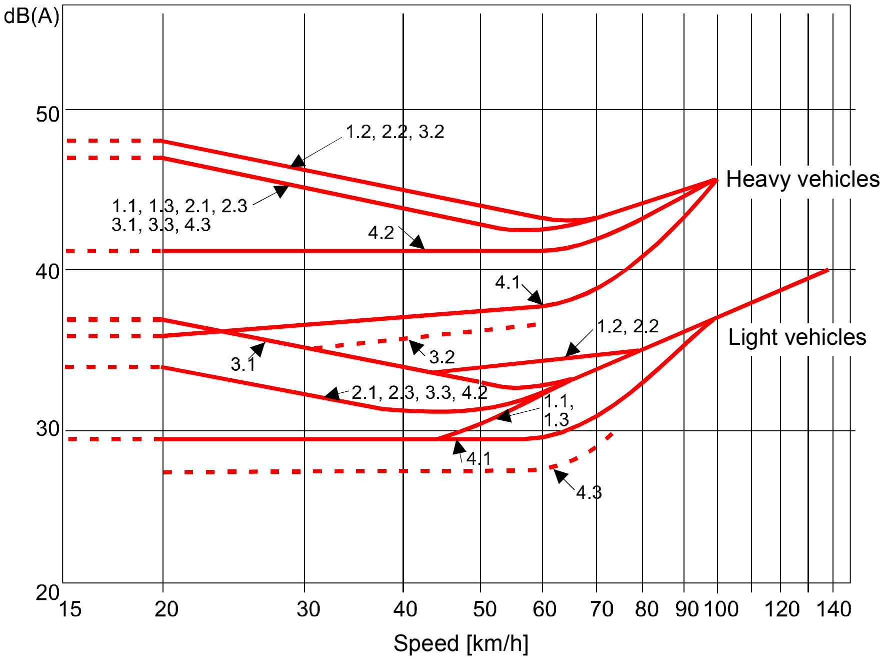


Figure 10: Noise emission values for light and heavy vehicles from [10]. Curves marked 1.i are for constant speed traffic flow, Curves 2.i for “pulsating” continuous flow, 3.i for “pulsating” accelerating traffic and 4.i for “pulsating” decelerating traffic. Curves j.1 are for horizontal roads, j.2 for up-hill and j.3 for downhill.

8. Emission variation with time

The noise emission may vary with time. New types of aircraft and of road and rail vehicles including their tyres and wheel thread appear from time to time, and source noise emission databases will have to be updated regularly.

Road and rail surface properties vary with time. As an example the noise levels from road traffic measured by DELTA [11] at the same time of the year during 7 or 8 years at five different dry road surfaces are shown in Figure 11. At an asphaltic concrete surface (AB12t REF in Figure 11) the noise level gradually increased by a few decibels during the first couple of years, due to compression of the wearing course and to wearing off of fine material leading to a rougher texture. Also at the drainage asphalts, denoted DA in the legend in Figure 11, the noise levels increased with time. A similar development takes place at railways where much higher noise levels are measured at corrugated than at newly ground track. The variation of the measurement results in Figure 11 includes variation in air and road surface temperature. The temperature variation, however, was sufficiently small to not affect the overall trend illustrated in the figure.

For the prediction of the road or rail traffic noise level L_{DEN} for a reference year it will have to be decided for which year of the lifetime of a road or a rail surface the calculation shall be made. Perhaps an average over the lifetime would be an appropriate choice.

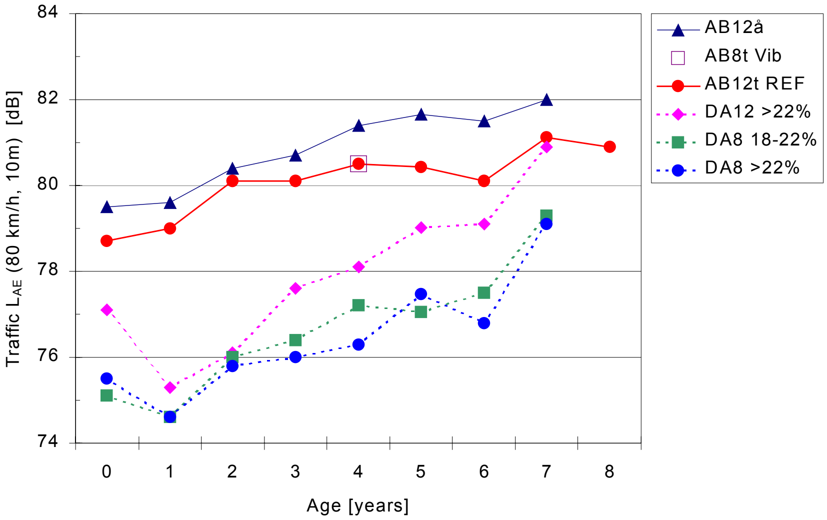


Figure 11: Noise level measured at five road surfaces at the same time of 7 or 8 consecutive years [11].

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