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Acoustic Source Modelling of Nordic Road Vehicles

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Abstract

The Harmonoise source model is analyzed based on Nordic data. The conclusion is that the Harmonoise source model is recommended with the following modifications and comments:

- New speed coefficients have been derived from Nordic data and some other coefficients have been modified as well
- Sweden, Norway and Finland get a regional correction for tyre/road noise to take into account different road surfaces and the use of studded tyres
- The horizontal directivity of rolling noise is modified to fall in between that of Nord 2000 and Harmonoise
- The correction for studded tyres has been modified
- The temperature corrections of Harmonoise have been confirmed
- The road gradient model for propulsion noise of heavy vehicles is verified

Key words: Source, model, road, vehicle, noise, acoustic, prediction

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Preface

This project has been financed by the Nordic road administrations. It is part of a larger project aiming at implementing a new prediction model for road traffic noise based on the Nord 2000 propagation model and the Harmonoise source model for road vehicles. It has been supervised and discussed by a project group consisting of Hans Jonasson (SP), Jørgen Kragh and Birger Plovsing (Delta), Svein Storeheier and Gunnar Taraldsen (SINTEF) and Ari Saarinen (VTT).

Summary

The Harmonoise source model is analyzed based on Nordic data. The conclusion is that the Harmonoise source model is recommended with some modifications. The recommended model to use for Nordic conditions is the following:

- Initially 3 vehicle categories are used: Passenger cars, medium heavy and heavy vehicles. Additional categories are defined in table 2.9. The medium heavy vehicle has two axles and the heavy vehicle has 3 or more axles. For heavy vehicles correction is made for the number of axles. A complete vehicle categorization is given in table 2.9. Default distributions between medium heavy and heavy vehicles are given in table 2.10 in case no better information is available.
- Each vehicle category is represented by two point sources, each having a specified sound power having contribution from tyre/road (rolling) and propulsion noise. Normally the source heights 0,01 m, 0,30 m and 0,75 m are used. Only two heights are used for each vehicle type. The lowest source is common for all vehicles whereas 0,30 m is used for category 1 vehicles only and 0,75 m for category 2 and 3 vehicles. The noise emission is separated into tyre/road (rolling) noise and propulsion noise. For heavy vehicles with high exhaust there is a fourth source height at 3,5 m. In case this source is used it is assigned all sound power of propulsion noise at and below 315 Hz.
- All default data refer to a reference condition: constant speed, 20 ˚C and the average of DAC 0/11 and SMA 0/11 road surface. Deviations from these conditions are corrected for.
- Default data for tyre/road noise is given by the equation $L_{WR}(f) = a_R(f) + b_R(f)\lg\left[\frac{v}{v_{ref}}\right]$. All coefficients are given in 1/3 octave bands 25-10000 Hz. The basic coefficients are given in table A.1. For Sweden, Norway and Finland regional corrections to a_R according to table A.2 are applied. The use of studded tyres are taken into account using eq. (8.1) and the coefficients of table A.3. No correction is applied for winter tyres without studs. 80% of tyre/road noise is associated with the lowest source and 20% with the highest one. The coefficients for heavy vehicles are derived from medium heavy vehicles by correcting for the number of axles according to eq. (2.2).
- Default data for propulsion noise is given by the equation $L_{WP}(f) = a_P(f) + b_P(f)\left[\frac{v - v_{ref}}{v_{ref}}\right]$. All coefficients are given in 1/3 octave bands 25-10000 Hz. The coefficients are given in annex A. For propulsion noise 80% is associated with the highest source and 20% with the lowest one.
- Tyre/road (rolling) noise is corrected for different road surfaces and different air temperatures. For normal road surfaces corrections to the coefficient a_R are made according to equation (2.3) for category 1 vehicles. If the road surface is younger than 2 years an additional correction is made according to eq. (2.4). No correction is made for other categories of vehicles. For temperatures other than 20ºC correction is made according to eq. (2.5) for category 1 vehicles. For category 2-4 only half of that correction is applied. It is also possible to correct for wetness according to eq. (2.6). User-defined road surface corrections can also be made,

see clause 8.3. For porous surfaces an ageing correction according to eq. (8.2) is applied.

- Propulsion noise is corrected for acceleration/deceleration and road gradients according to eq. (2.8).
- All point sources are assigned a specific frequency dependent vertical directivity with the main purpose to take the screening of the car body into account. This directivity is given in table 2.4.
- The lowest point source is assigned a specific frequency dependent horizontal directivity with the main purpose to take the horn effect of the tyre/road source into account. This directivity is given by eq. (2.12).
- The 0,75 m point source for propulsion noise of heavy vehicles is assigned a frequency independent horizontal directivity. This directivity is given by eq. (2.11).
- The maximum sound pressure level is the highest instantaneous sound pressure level during pass-by of a single vehicle including directivity and propagation effects. The maximum sound pressure levels are calculated from the sound power levels which are energy mean values. For statistical treatment these are transferred to arithmetic mean values using eq. (2.13). Short distance effects of time-weighting and vehicle length are ignored. If relevant the per cent exceedance level is calculated using eq. (2.16). Default values for the standard deviation of the sound power level of different categories of vehicles are given in (2.14) and (2.15) for light and heavy vehicles respectively.
- Propagation effects are taken into account by assigning different acoustic impedances to different road surfaces. Suitable default values for some road surface impedances are given in table 10.1.

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1 Introduction

In 2001 the Nord 2000 project was finalized, [1]. The road vehicle acoustic source model of that project was used as a starting point for a corresponding European project, Harmonoise, [2]. The Harmonoise project achieved further improvements of the source model, the most important one being the complete separation of the generation of tyre/road noise and propulsion noise. This was considered to be such a major improvement that the Nordic road authorities decided to implement the Harmonoise source model for Nordic road traffic noise predictions. However, it was also recognized that some of the contents of the Harmonoise source model, such as the coefficients used for sound power determinations, had to be reviewed and, if necessary, better adapted to Nordic conditions.

In this report the Harmonoise source model is reviewed taking some new Nordic measurements into account, some of them carried out within the frame av a European follow-up project to Harmonoise, Imagine, [3].

2 Basic source model

2.1 General

The starting point below is the Harmonoise source model. Unless specifically pointed out and discussed this model will be used also for Nord 2000.

2.2 Point sources

The road vehicle has to be modelled as point sources. In Nord 2000, [1], 3 source heights with equal distribution of sound power are always used: 0,01 m, 0,15 m and 0,30 m. In Harmonoise, [2], the source heights 0,01 m, 0,30 m and 0,75 m are used. However, only two heights are used for each vehicle type. The lowest source is common for all vehicles whereas 0,30 m is used for category 1 vehicles only and 0,75 m for category 2 and 3 vehicles. The noise emission is separated into tyre/road (rolling) noise and propulsion noise. 80% of tyre/road noise is associated with the lowest source and 20% with the highest one. For propulsion noise 80% is associated with the highest source and 20% with the lowest one.

There is no difference in computational speed between Harmonoise and Nord 2000 as the sound propagation has to be calculated for 3 sources in both cases. However, as the analysis of transfer functions in clause 3 and the Harmonoise investigations, [1], indicate that the tyre/road noise source is indeed very low and that the results improve a little if we don't spread out the sound power too much vertically it seems reasonable to adopt the later Harmonoise approach. In both cases the sources are located at the nearest wheels and not under the middle of the car. This means that the sources are located 0,75 m and 1,25 m in front of the centre line of the vehicle for light and heavy vehicles respectively. For practical reasons it will be assumed that this distance equals to 1,0 m for all vehicles. For heavy vehicles with high exhaust both Nord 2000 and Harmonoise have an additional source at 3,5 m. The approach in this case is to assign all frequencies with midband frequency at and below 315 Hz to this high location as exhaust noise is a typical low frequency phenomenon.

2.3 Tyre/road noise

2.3.1 Reference condition

HARMONOISE uses the reference temperature t= 20ºC and a virtual reference road surface consisting of a mixture of DAC 0/11 and SMA 0/11 with an age of 2 years or more but not at the end of its life time. Corrections to other temperatures and some other road surfaces are given, see 2.3.3.

2.3.2 Sound power level of the reference condition

Harmonoise assumes the following relationship:

$$L_{WR}(f) = a_R(f) + b_R(f)\lg\left[\frac{v}{v_{ref}}\right] \tag{2.1}$$

where v_{ref}= 70 km/h. The coefficients $a_R(f)$ and $b_R(f)$ for each main vehicle category is given in tables. The values are intermediate values and a definite set of coefficients will be developed within the framework of the IMAGINE project, www.imagine-project.org , and are expected around December 2006. The Harmonoise coefficients will be analyzed later in this report. The difference between category 2 and category 3 is a function of the number of axles. It is assumed that L_{WR} increases as 10 lg(number of axles). Heavy city buses will often have 3 axles and long distance freight traffic will on average have at least 5 axles. In Sweden where longer vehicles are permitted it is not unusual with 7 axles and there the average number is close to 6. The equation to use is

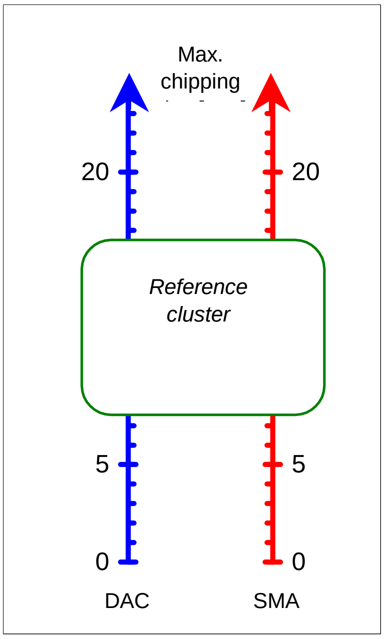
$$(a_R)_{Category3} = (a_R)_{Category2} + 10\lg\left(\frac{numberofaxles}{2}\right) \tag{2.2}$$

2.3.3 Corrections to the reference condition

For the most common types of road surfaces: DAC and SMA with chip sizes 8-16 mm Harmonoise uses a simple frequency independent correction shown in figure 2.1. Relative to the reference condition the correction is

$$\Delta L_{Road} = RS + 0{,}25\ (CS-11)\ dB \tag{2.3}$$

where RS = -0,3 for a DAC-surface and +0,3 for an SMA-surface and CS = maximum chipsize, in mm. The range of validity is chip sizes between 8 and 16 mm.



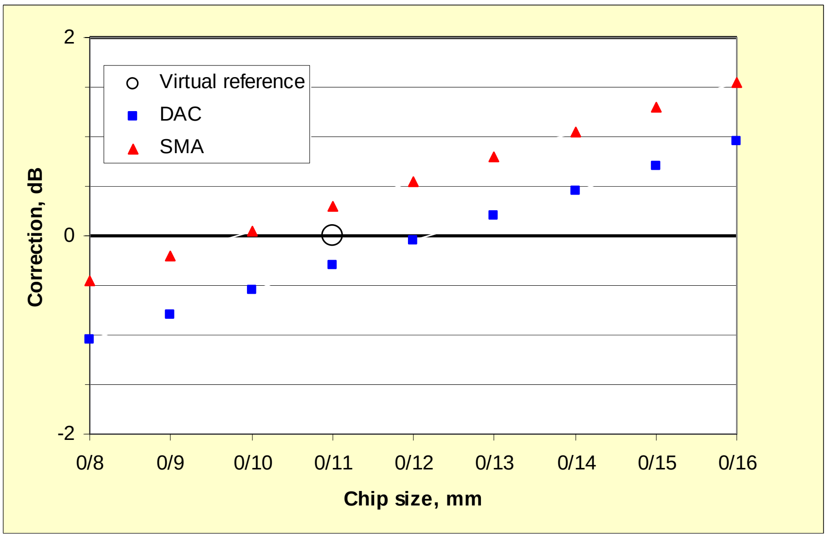


Figure 2.1 Corrections to use for different reference surfaces

For surfaces younger than 2 years the noise level is lower and correction can be made according to

$$-(0{,}2T^2 - 1{,}2T + 1{,}6); T \leq 2\,years \qquad (2.4)$$

There is also a correction due to temperature given by

$$L_{WR}(\theta) = L_{WR}(\theta_{ref}) + K(\theta_{ref} - \theta) \qquad (2.5)$$

L_{WR} = sound power level due to rolling noise, dB
θ = the measured air temperature, ºC
θ_{ref} = the reference air temperature, 20ºC
K = the temperature coefficient given in table 2.1 below

Please note that the air temperature is used. If the road surface temperature is used the coefficients *K* given in table 2.1 taken from Harmonoise are no longer valid. Most of the road surfaces listed in the table are not used in the Nordic countries.

Table 2.1 Temperature coefficient K for different surfaces, air temperature

Main acronym	***Detailed acronym*** *Common variants for different aggregate compositions (maximum chipping size, etc)*	***Surface description***	***Temperature coefficient (air)*** ***(divide by 2 for vehicle categories 2-4)***
		Bituminous mixes ("asphalt" surfaces)	
DAC	DAC 0/8, DAC 0/11, DAC 0/14, DAC 0/16	Dense asphalt concrete	0.10
SMA	SMA 0/8, SMA 0/11, SMA 0/14, SMA 0/16	Stone mastic asphalt	0.06
OGAC	OGAC 4/8, OGAC 6/11, OGAC 8/14, OGAC 8/16	**Open-graded asphalt concrete, voids 15-19 % (when new)**	0.05 (if ≤ 1 yr) 0.06 (if > 1 yr)
PAC	PAC 4/8, PAC 6/11, PAC 8/14, PAC 8/16	**Porous asphalt concrete (single-layer), voids ≥20 % (when new)**	Up to and incl PAC 6/11: 0.05 (if ≤ 2 yr), 0.06 (if > 2 yr) Above PAC 6/11: 0.04 (if ≤ 2 yr), 0.06 (if > 2 yr)
DPAC	DPAC 4/6+8/11, DPAC 4/8+11/16, PAC 6/11+11/16	**Porous asphalt concrete (double-layer)**	0.05 (if ≤ 2 yr) 0.06 (if > 2 yr)
GA	GA 5/8, GA 8/11	Gussasphalt = mastic asphalt, surface common in Germany, usually has chippings rolled into it	GA 5/8: 0.10 GA 8/11: 0.06
HRA	HRA 8/11, HRA 11/16	Hot rolled asphalt, surface common in the U.K., always has chippings rolled into it	0.06
THS	THSDAC 0/6, THSDAC 0/8, THSSMA 0/6, THSSMA 0/8	Thin surfacing (non-proprietary), based on either a DAC or SMA mix	0.10
ISO-S		Reference smooth surface according to ISO 10844	0.08
ISO-R		Reference rough surface according to ISO 10844	0.12
		Rubberized surfaces	
DACR	DACR6 0/11	Asphalt rubber = DAC surface with rubber added (>2% and <20% by weight)	0.10
PERS	PERS 50, PERS 85	Poroelastic road surface (≥20 % by weight is rubber)	0.06
		Surface dressings (often called "chip seals")	
SDS	SDS 4/8, SDS 8/11, SDS 11/16	**Surface dressing (single)**	0.12
SDD	SDD 4/8+8/11, SDD 8/11+11/16	**Surface dressing (double)**	0.12
		Cement concrete (often called just "concrete")	
CC	CC 0/8, CC 0/11, CC 0/14, CC 0/16, CC 0/22	Cement concrete (often referred to as just "concrete") – untreated	0.05

Correction is only applied for wet surfaces, that is when there is a layer of water on the road. The correction is only made for high frequencies and passenger cars. The increase ΔL_{wet} relative a dry surface is given by:

$$\Delta L_{wet} = 10\lg\left(\frac{110}{v}\right) + 20\lg\left(\frac{f}{2000}\right), f > 2000 \text{ Hz}, 30 < v < 110 \qquad (2.6a)$$

$$\Delta L_{wet} = 5\lg\left(\frac{110}{v}\right), f = 1600 \text{ Hz} \qquad (2.6b)$$

$$\Delta L_{wet} = 2{,}5\lg\left(\frac{110}{v}\right), f = 1250 \text{ Hz} \qquad (2.6c)$$

No corrections are introduced for heavy vehicles as there is not yet sufficient data available to draw any firm conclusions.

2.4 Propulsion noise

For propulsion noise Harmonoise assumes the following relationship when driving at a constant speed:

$$L_{WP}(f) = a_P(f) + b_P(f)\left[\frac{v - v_{ref}}{v_{ref}}\right] \qquad (2.7)$$

where v_{ref}= 70 km/h. The coefficients $a_P(f)$ and $b_P(f)$ for each main vehicle category are given in tables. The values are intermediate values and a definite set of coefficients will be developed within the framework of the IMAGINE project, www.imagine-project.org , and are expected around December 2006. The Harmonoise coefficients will be analyzed later in this report.

Correction for acceleration/deceleration is given by

$$\Delta L_{acc} = C \cdot a \text{ ; -2 m/s}^2 \leq a \leq 2 \text{ m/s}^2 \qquad (2.8)$$

where a = the acceleration (a>0)/deceleration (a<0) in m/s^2 and the coefficient C is given by table 2.2. For category 3 vehicles applying engine brake the unsigned value of the acceleration a shall be used. Such will often be the case under steep and long downhill conditions. The correction is made equally at each band frequency for the propulsion noise coefficients a_P. Gradients are treated accordingly, that is the downward component of the gravity (a=10 sin(δ) where δ= the angle of the ramp) is treated as an equivalent acceleration/deceleration.

Table 2.2 Acceleration/deceleration coefficient in eq. (2.8).

Vehicle category	C
Category 1	4,4
Category 2	5,6
Category 3	5,6

2.5 Directivity

According to both Nord 2000 and Harmonoise the directivity relative the pass-by integrated equivalent sound power level is given by

$$\Delta L(f,\varphi,\psi) = \Delta L_H(f,\varphi) + \Delta L_V(f,\psi) \qquad (2.9)$$

where the angles are given by figure 2.2.

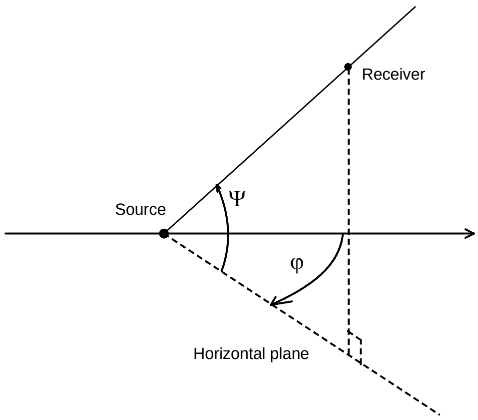


Figure 2.2 Geometry for the directivity functions).

Nord 2000 has only horizontal directivity whereas Harmonoise has both horizontal and vertical directivity. The horizontal directivity of Nord 2000 is given by table 2.3.

Table 2.3 Passenger cars. Horizontal directivity, see figure 2.3.

	Height	**Frequency range**	**Directivity**
Source 1	0,01 m	1600 - 10000 Hz	-5 + 7 abs(cos(φ))
Source 2	0,15 m	1600 - 10000 Hz	-5 + 7 abs(cos(φ))
Source 3	0,30 m	1600 - 10000 Hz	-5 + 7 abs(cos(φ))

Harmonoise has the following horizontal directivity:

For the point source at the height 0,01 m the following horizontal directivity is to be used

$$\Delta L_H(\varphi) = 0;\ f \le 1250\ Hz,\ f \ge 8000\ Hz \qquad (2.10a)$$

$$\Delta L_H(\varphi) = (-1{,}5 + 2{,}5 \cdot abs(\cos(\varphi)))\sqrt{\cos(\psi)};1600 \le f \le 6300 Hz \qquad (2.10b)$$

For the point source at height 0,3 m the following horizontal directivity is to be used

$$\Delta L_H = 0 \qquad (2.10c)$$

For the point source at height 0,75 m the following horizontal directivity is to be used

$$\Delta L_H(\varphi) = (1{,}546 \cdot (pi/2-\varphi)^3 - 1{,}425(pi/2-\varphi)^2 + 0{,}22(pi/2-\varphi) + 0{,}6)\sqrt{\cos(\psi)}$$

(in radians) (2.11)

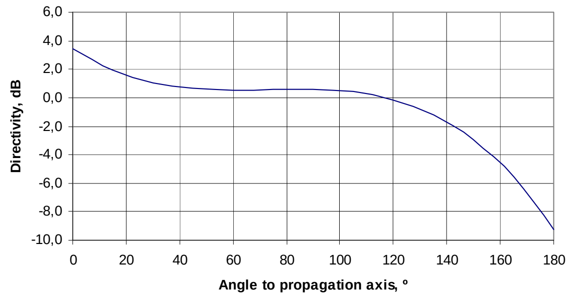


Figure 2.3 Horizontal directivity according to Nord 2000 and Harmonoise as a function of the angle to the vehicle axis (direction of propagation of the vehicle)

Eq. (2.11) is illustrated in figure 2.3.

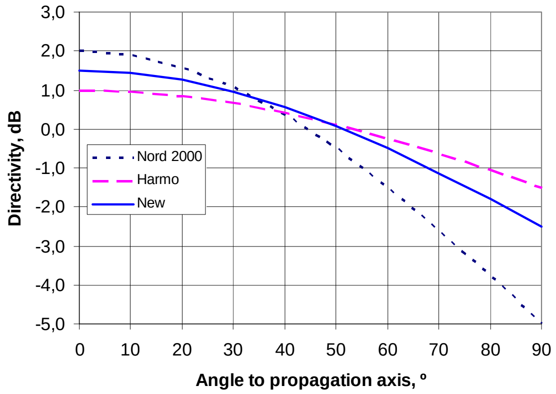


Figure 2.4 Horizontal directivity according to Nord 2000 and Harmonoise as a function of the angle to the vehicle axis (direction of propagation of the vehicle). There is symmetry between the two sides of the normal.

As to horizontal directivity of rolling noise we have little reliable data. As is shown in figure 2.5 a recent measurement on a coasting Volvo V70 clearly indicates that there is indeed a directivity. The simulation using 2 sources 4m apart falls off quicker than the measurement results. There are, however, indications that Nord 2000 has too high a directivity and in Harmonoise it was decided to have a little less directivity, see figure 2.4 for comparison. In clause 2.6 a large number of pass-by measurements are analyzed with respect to the difference between L_{EA} and L_{FAmax} and it seems that a better fit is obtained with the function (New in figure 2.4):

$$\Delta L_H(\varphi) = 0;\ f \leq 630\ Hz,\ f \geq 8000\ Hz \tag{2.12a}$$

$$\Delta L_H(\varphi) = (-2{,}5 + 4 \cdot abs(\cos(\varphi)))\sqrt{\cos(\psi)};800 \leq f \leq 6300 Hz \tag{2.12b}$$

Observe that the directivity is expanded downwards in frequency compared to that of both Nord 2000 and Harmonoise. The $\sqrt{\cos(\psi)}$ has been introduced to avoid numerical problems with integration when the receiver is above the vehicle.

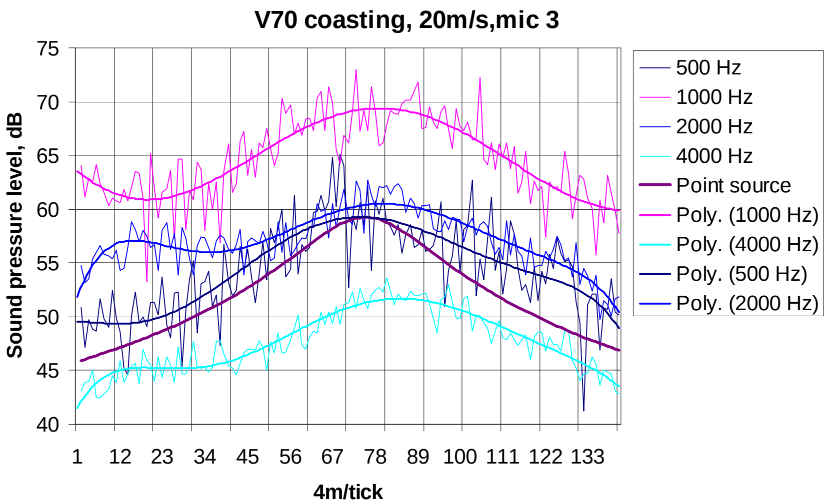


Figure 2.5 Time history of a Volvo V70 coast by at 70 km/h (20m/s)

As to vertical directivity in Harmonoise it is given by table 2.4. These data should be reasonably reliable as they are based on many measurements carried out by Autostrade in Italy.

Table 2.4 Functions approximating the vertical directivity $\Delta L(\psi)$

Freq./source height	hs=0,01m	hs=0,3m	hs=0,75m
50,63,80	0	-2sin(ψ)	0
100,125,160	0	-4sin(ψ)	0
200,250,315	-2(1-cos²(ψ)	-5(1-cos²(ψ)	-2(1-cos²(ψ))
400,500,630	-3(1-cos²(ψ)	-5(1-cos²(ψ)	-3(1-cos²(ψ))
800,1000,1250	-4(1-cos²(ψ)	-6(1-cos²(ψ)	-3(1-cos²(ψ))
1600,2000,2500	-4(1-cos²(ψ)	-6(1-cos²(ψ)	-2(1-cos²(ψ))
3150,4000,5000	0	-5(1-cos²(ψ)	-2(1-cos(ψ))
6300,8000,10000	0	-8(1-cos(ψ))	-2(1-cos(ψ))

2.6 Maximum sound pressure levels

Traditionally, in the Nordic countries, the maximum level is the maximum level from a single individual vehicle and not from a combination of vehicles. This maximum sound pressure level shall be calculated from the sound power level, which is an energy mean value. For statistical reasons this mean value should be converted to the arithmetic mean value. For a normal distribution with the standard deviation σ the relationship between energy mean value L_{em} and arithmetic mean value $\overline{L}$ is given by

$$L_{em} - \overline{L} = 0{,}05\ln(10)\cdot\sigma^2 \qquad (2.13)$$

Eq. (2.13) is illustrated in figure 2.6.

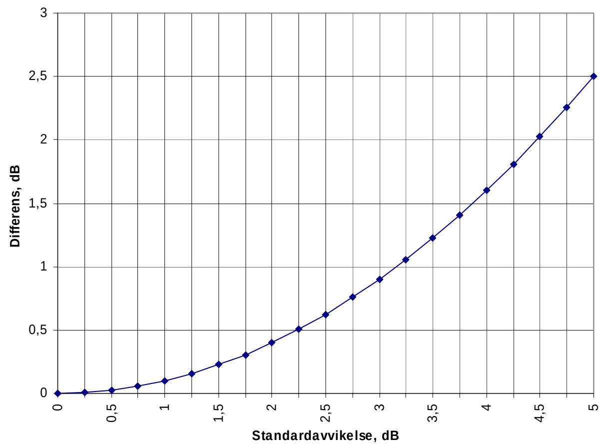
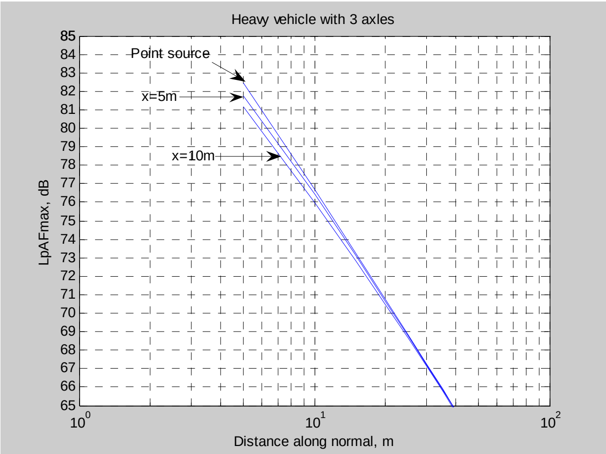


Figure 2.6 Difference between energy mean value and arithmetic mean value for a normal distribution

When calculating L_{eq}-values for moving sources we don't have to bother about the horizontal distribution of the sound sources for a long vehicle. However, if we want to determine the maximum level at short distances this has to be considered. The problem is illustrated by figure 2.7 below based on equal distribution of the total sound power level between the different wheel axles. We can see that a point source model overestimates the sound pressure level at distances below about 20 m. However, as this overestimate is always less than 2 dB and as engine noise is important for heavy vehicles it seems reasonable to ignore this difference and assume a point source when carrying out calculations.



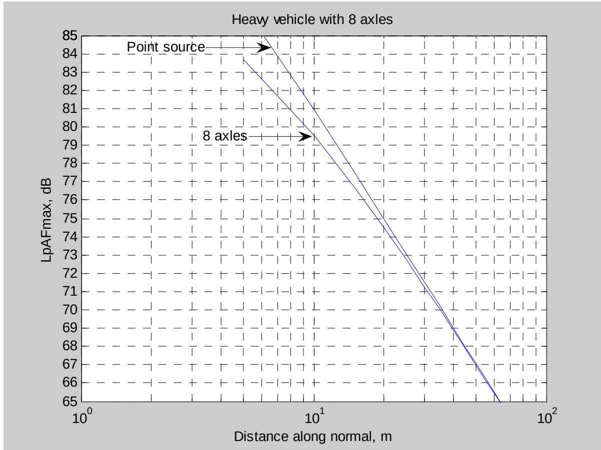


Figure 2.7 Difference between sound propagation from a point source and an extended source consisting of one point source at each axle.

Another problem to consider for predictions is the integration time at short distances. Figure 2.8 shows what happens with a point source passing by at a short distance of 6,75m corresponding to the wheels of a passenger car at the standard measurement distance of 7,5m. The sound power of the source has been kept constant for all speeds. We can see that time-weighting *F* is too slow to yield the true maximum level above about 30 km/h. However, if we select 70 or 80 km/h as reference speed the error will be within $\pm$ 0,3 dB which is quite acceptable for the short distance of 6,75 m. For longer distances this effect will decrease and can thus be disregarded.

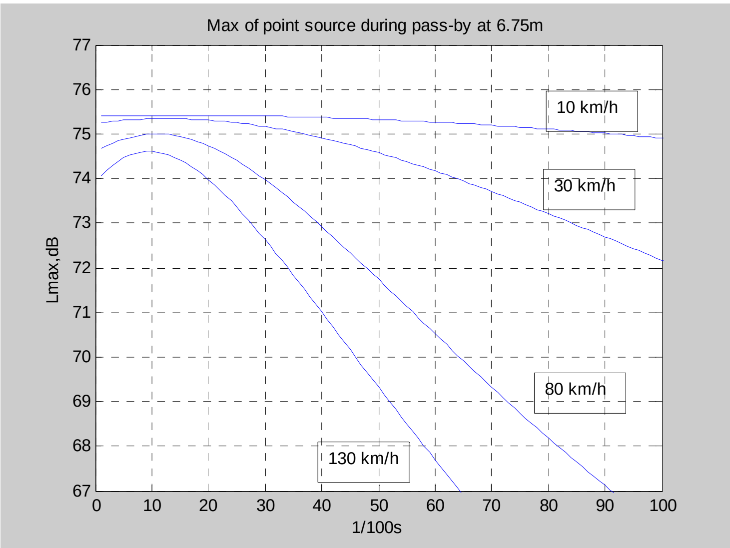


Figure 2.8 Theoretically calculated pass-by maximum sound pressure level from a point source moving with different speeds using time-weighting F

Another problem is the directivity of the source. If it radiates more sound in the forward and backward direction than perpendicular to the propagation path the maximum level will be less than the one calculated using a point source. If we calculate the difference between L_E and L_{max} for a point source at 6,75m on a reflecting plane we get the result shown in table 2.5 which can be compared with the measured results in table 2.6.

Table 2.5 calculated difference for category 1 vehicles using two directional sources.

Speed	Calculated L_E-L_{max}				
	1 omnidirectional source	2 omnidir. sources 4m apart	Harmonoise directivity	Nord 2000 directivity	New directivity
75	-0,1	0,2	1,0	2,3	1,5
80	-0,4	-0,1	0,7	2,0	1,2
85	-0,6	-0,3	0,5	1,8	1,0

Table 2.6 Measured differences between L_{EA} and L_{pFAmax}

Cat. 1A/7,5m			
SEL-Lmax	Stddev	Speed	Num veh
1,8	0,6	74,2	21
1,1	0,6	85,4	30
1,2	0,6	92,1	8
Cat.3B/7,5m			
0,7	0,5	79,6	5
Cat.3D/7,5m			
1,3	0,6	78,2	5

Table 2.5 indicates that the truth is a little in between Nord 2000 and Harmonoise. A better fit is achieved by the “New” function shown in clause 2.5. The interpretation for category 1 vehicles is rather straightforward as the sound power level is dominated by tyre/road noise. For heavy vehicles it is more complicated. A comparison between the calculations in table 2.7 and the measurements in table 2.6 shows that the calculated values are about 0,5 dB higher. As propulsion noise also contributes significantly it does not contradict the directivity model for rolling noise.

Table 2.7 Measured differences between L_{EA} and L_{pFAmax}

Speed	Calculated L_E-L_{max}	
km/h	Omni sources	New directivity function
80-3sources	0,4	1,3
80 -8 sources	1,7	1,8

As both tyre/road noise and propulsion noise for heavy vehicles are directional the maximum sound pressure level will normally not occur at the shortest distance to the receiver but rather a little earlier. Screens and changes in terrain topography can also affect L_{AFmax}. Thus it is necessary to determine the instantaneous level of a passing vehicle as a function of angle and then determine the highest of the instantaneous level to get the maximum.

In Swedish noise regulations the requirement is that a certain L_{AFmax} must not be exceeded more than a certain number of times, normally 5 times. In order to calculate this level the statistical distribution of L_{AFmax} has to be known. Assuming a Gaussian distribution it can then be determined using figure 2.9.

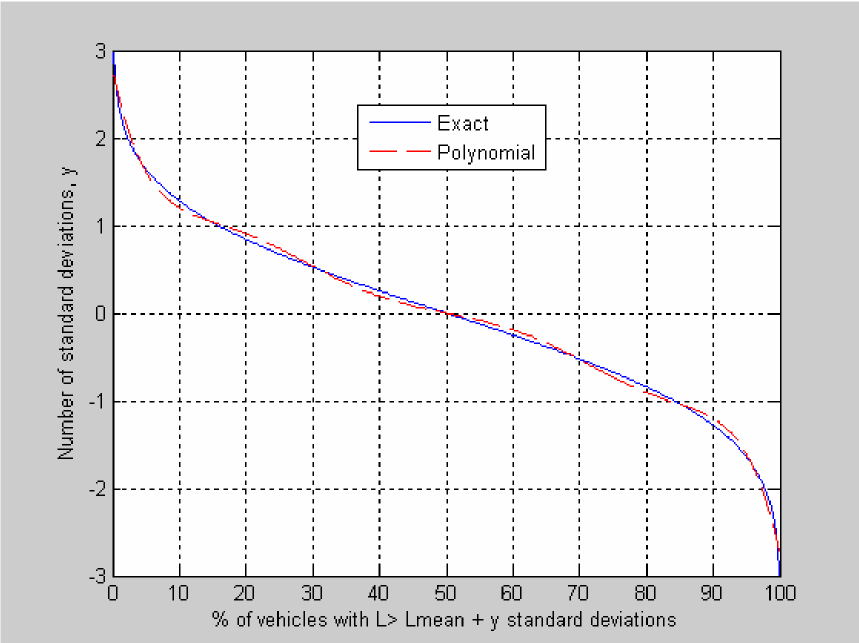


Figure 2.9 Function y=P(x). Percentage of single events with a maximum sound pressure level exceeding, by a certain number y of standard deviations, the (arithmetic) mean of a normal distribution of maximum sound pressure levels

Figure 2.9 can be approximated by the polynomial $P(x)$ given in table 2.8.

Table 2.8 Polymonial P(x) approximating figure 2.9.

Coefficient	
-0.00000000001130	x^7
0.00000000395695	x^6
-0.00000055493824	x^5
0.00003978754303	x^4
-0.00154675475318	x^3
0.03207776088465	x^2
-0.35743879311349	x
2.76935096017743	

As to standard deviation of the maximum level, in case no better information is available, the following values can be used (from [13]):

$$s(heavy) = 4{,}1\,;\; 30 \le v \le 50 \text{ km/h} \tag{2.14}$$

$$s(heavy) = 10 \cdot e^{-0{,}9\frac{v}{50}},\; v > 50 \text{ km/h}$$

$$s(light) = 5{,}5 \cdot e^{-0{,}7\frac{v}{50}},\; \text{v} \ge 30 \text{ km/h} \tag{2.15}$$

The standard deviation will increase if the speed variation on the road under consideration increases. The n^{th} highest level of N vehicles passing by during a specified time period is given by

$$L_{AF\max,n} = \overline{L_{AF\max}} + P(\frac{100 \cdot n}{N}) \cdot s \tag{2.16}$$

2.7 Vehicle categories

2.7.1 Categorization

The Harmonoise categorization is shown in table 2.9. It is very similar to that of Nord 2000 but as it will probably be used all over Europe it seems reasonable to adopt this categorization.

Table 2.9 Summary of vehicle categories to be used in HARMONOISE. Note that this table is primarily for the data collection phase of the project. When it comes to the final model, one must take the availability of vehicle data for a certain road into consideration.

Main category (type)	No.	Sub-categories: Example of vehicle types	Notes
Light vehicles	**1a**	**Cars (incl MPV:s up to 7 seats)**	**2 axles, max 4 wheels**
	1b	**Vans, SUV, pickup trucks, RV, car+trailer or car+caravan(1), MPV:s with 8-9 seats**	**2-4 axles(1), max 2 wheels per axle**
	1c	**Electric vehicles, hybrid vehicles driven in electric mode(2)**	**Driven in combustion engine mode: See note**
Medium heavy vehicles	**2a**	**Buses**	**2 axles (6 wheels)**
	2b	**Light trucks and heavy vans**	**2 axles (6 wheels)(3)**
	2c	**Medium heavy trucks**	**2 axles (6 wheels)(3)**
	2d	**Trolley buses**	**2 axles**
	2e	**Vehicles designed for extra low noise driving**	**2 axles(5)**
Heavy vehicles	**3a**	**Buses**	**3-4 axles**
	3b	**Heavy trucks(4)**	**3 axles**
	3c	**Heavy trucks(4)**	**4-5 axles**
	3d	**Heavy trucks(4)**	**≥6 axles**
	3e	**Trolley buses**	**3-4 axles**
	3f	**Vehicles designed for extra low noise driving**	**3-4 axles(5)**
Other heavy vehicles	**4a**	**Construction trucks (partly off-road use)(4)**	
	4b	**Agr. tractors, machines, dumper trucks, tanks**	
Two-wheelers	**5a**	**Mopeds, scooters**	**Include also 3-wheel motorcycles**
	5b	**Motorcycles**	

(1) 3-4 axles on car & trailer or car & caravan

(2) Hybrid vehicles driven in combustion engine mode: Classify as either 1a or 1b

(3) Also 4-wheel trucks, if it is evident that they are >3.5 tons

(4) If a high exhaust is noted, identify this in the test report. Categorize this as 3b', 3c', 3d' or 4a'

(5) For example, there are some delivery trucks designed for extra low noise (meeting more stringent standards than the current EU limiting levels) combined with a driving mode called "Whisper mode" making it possible to drive in a residential area with much lower noise emission than for a conventional delivery truck. All trucks and buses especially designed in accordance with these ideas are counted in this category.

2.7.2 Default data to use when information is missing

In [11] the proposal shown in table 2.10 is given in case data on heavy vehicles are not subdivided into 2 categories.

Table 2.10 Default distribution between category 2 and 3 vehicles according to [10].

Type of road	Default proportion if distinction is made	
	Cat. 2	Cat. 3
Major road with high proportion of heavy transit traffic (e.g. E-type motorways)	10 %	90 %
Urban streets (excluding streets carrying a substantial through traffic)	90 %	10 %
All other roads (roads and streets not identified as belonging to the types above)	40 %	60 %

[1)] This case assumes that there is no distinction made between various road types; implying that the simplified default values of the table on the previous page are used.

Table 2.10 can be used when no better data are available.

2.8 Road description

When collecting new data the information given in table 2.11 should be recorded.

Table 2.11 Information to record when collecting data.

Measure or description	**Example**	**Notes**
Basic surface type , see 5.2.2	DAC, SMA,	Man
Maximum chipping size	11 mm, 16 mm	Man
Grading curve of mix	(Percent passing by sieve size)	Opt
Age of the surface	4 years	Man
Total traffic exposure (No. of axles passing)	3 300 500 axles	Opt
Composition of traffic (% of heavies, % of studded tyres)	11 % heavies, 55 % of tyres are studded in wintertime	Opt
Posted speed limit	70 km/h	Man
Type of road, measured lane	Motorway, 2x3 lanes, rightmost lane	Man
Grade (longitudinal slope)	2,5 %	Opt
Condition of surface (subjective, incl homogeneity)	Surf in partly worn cond., tracks visible but not deep, lateral variation clearly visible, binder worn away in wheel tracks only	Man
Surface texture - MPD (ISO 13473-1) Surface texture - L_{T63} (ISO 13473-2) Surface texture - L_{T4} (ISO 13473-2)	1,03 mm 0,87 mm 0,57 mm	Opt Opt Opt
Sound absorpt coeff as a function of freq (ISO 13472-1)* or impedance	Sound absorp coeff versus frequency or impedance or parameters according to a certain impedance model	Opt
Unevenness (CEN prEN 13036-x)	2,2 IRI	Opt

* Applicable only to potentially porous surfaces. Man = Mandatory. Opt = Optional

3 Some uncertainties associated with current emission data

In the current Nord 2000 data bank of sound power levels the sound power levels have been derived from pass-by measurements of the the sound exposure level, L_E. In this derivation the following equation was used:

$$L_W = L_{E,10m} + C(50) + 10\lg\left(\frac{v}{50}\right) \tag{3.1}$$

where $C(50)$ is a transfer function calculated for 2 different heights of microphone, 0,2m and 4,0m. For each calculation the sound power level was divided between three point sources at the heights 0,01m, 0,15m and 0,3m. The different transfer functions used are shown in figure 3.1. According to the test method NT ACOU 109, [9], the position yielding the highest sound power level shall be used. For Swedish data the highest position was normally used whereas it was quite common to use the lowest position for the Danish data. A later analysis of measured data indicates that these transfer functions are not equally reliable. Figure 3.2-3.4 show some measured examples of the measured differences between 4,0 m and 0,2 m microphone heights.

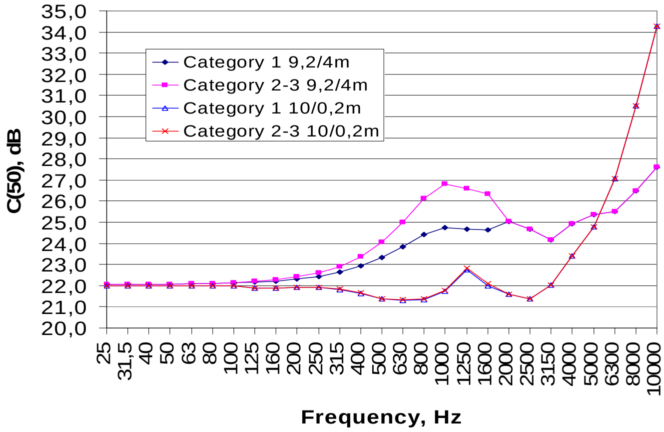


Figure 3.1 The transfer functions C(50) according to Nord 2000

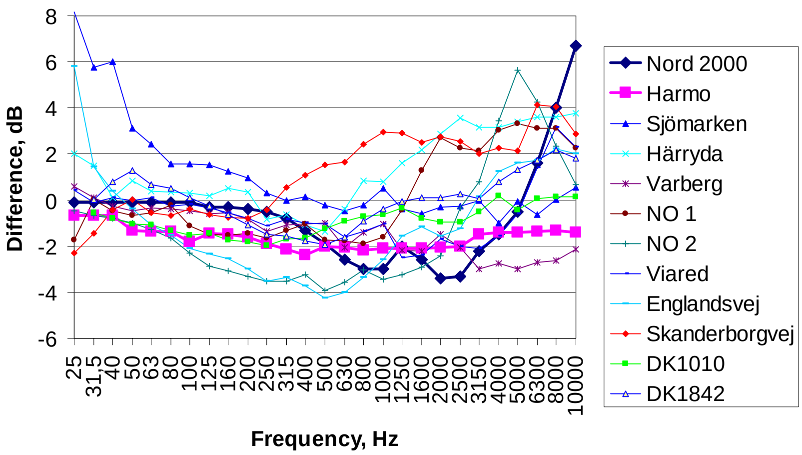


Figure 3.2 Category 1 vehicles. The difference between SEL at 4 m and SEL at 0,2 m height according to measurements compared to Nord 2000 and Harmonoise respectively.

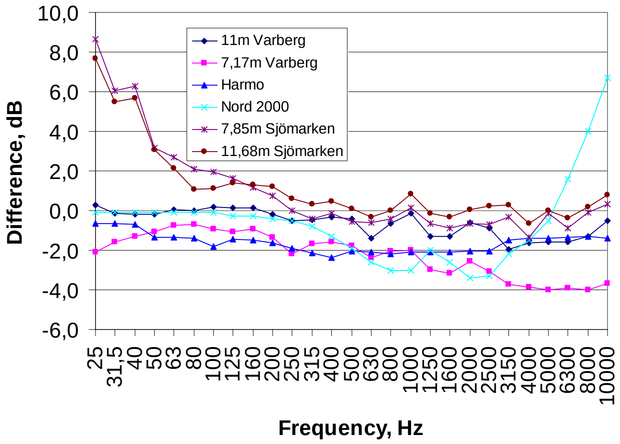


Figure 3.3 Category 1 vehicles. The difference between SEL at 4 m and SEL at 0,2 m height according to measurements compared to Nord 2000 and Harmonoise respectively. Different distances at two sites.

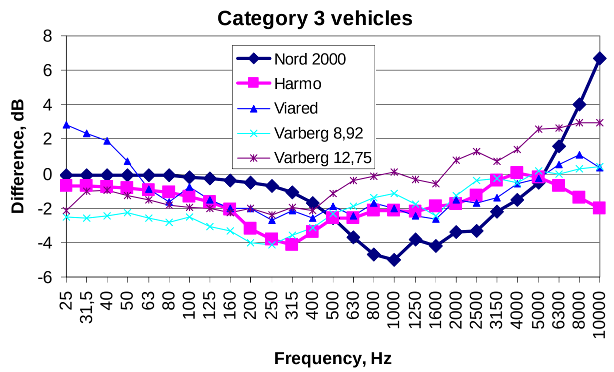


Figure 3.4 Category 3 vehicles. The difference between SEL at 4 m and SEL at 0,2 m height according to measurements compared to Nord 2000 and Harmonoise respectively.

Conclusions:

The great variations in the difference between the two transfer functions indicate an uncertainty when applying these functions. The uncertainty is likely to be highest for the lowest microphone height as this is likely to be most sensitive to varying conditions. A particular risk is that the 0,01 cm source is screened when the microphone is at one side of the road whereas the pass-by is at the other side. For category 1 vehicles Nord 2000 is much more sensitive for the transfer functions than Harmonoise as more power is allocated to the higher source locations.

Because of these problems with the transfer functions all old measurements have been converted back to sound exposure level at 10m and 4m height and then these data have been used. When converting back the transfer function has been the same as the one used originally.

4 Harmonoise versus Nord 2000

4.1 Category 1 vehicles

In figure 4.1 and 4.2 the differences between Nord 2000 and the first version of Harmonoise is shown. It is obvious that the speed dependence between Nord 2000 and Harmonoise is too different to be acceptable. The Swedish and Danish data are very similar in speed dependence although the Swedish levels are significantly higher. This later difference might, however, be explained by different road surfaces.

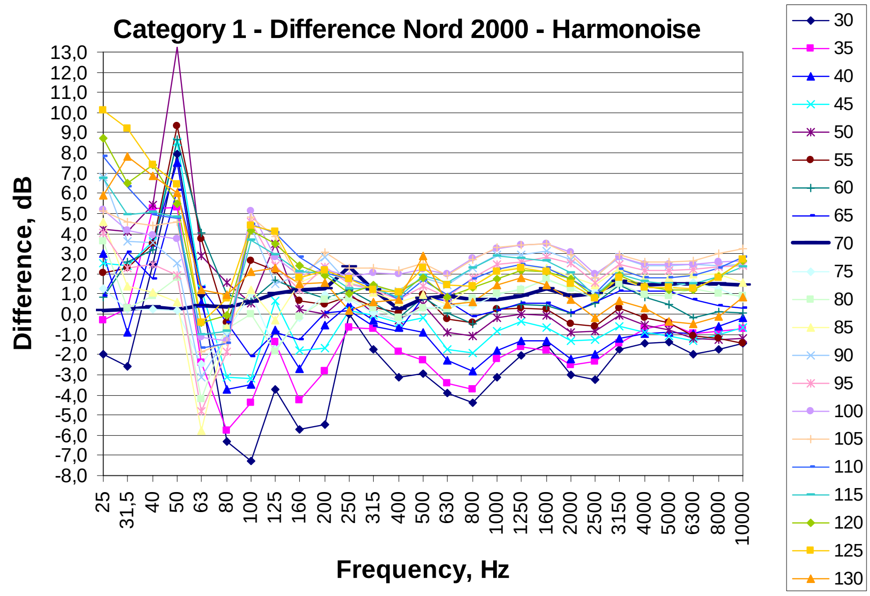


Figure 4.1 Mean difference in L_{EA} = 0,9 dB, s= 1,7 dB

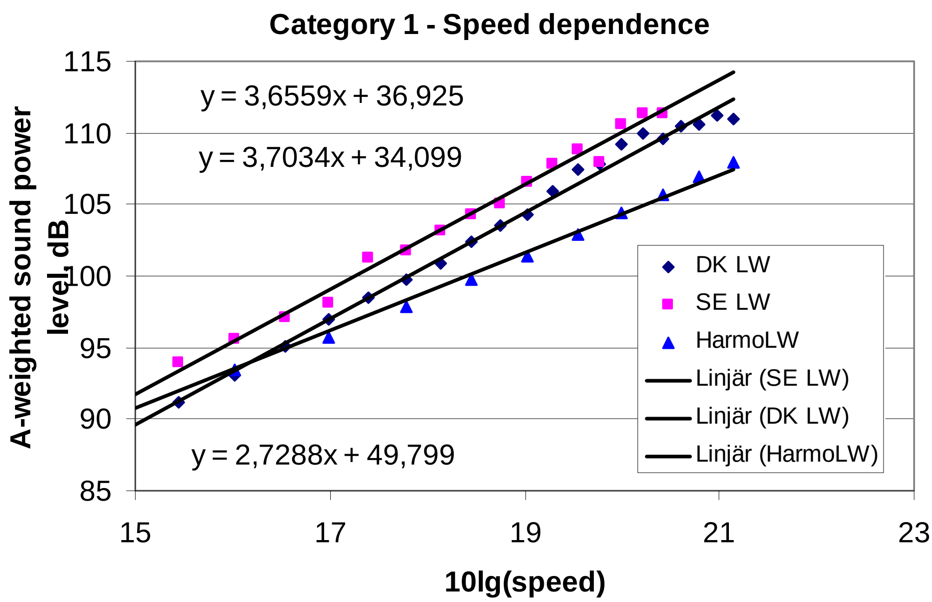


Figure 4.2 Regression analysis of A-weighted sound power levels of Danish, Swedish and Harmonoise values in Nord 2000, [1].

From figure 4.2 we can see that the speed coefficient of Harmonoise is considerably smaller than that of the Nordic Nord 2000 measurements. From data reported in [5] we can see that almost any speed coefficient is possible but that modern data seem to come rather close to 35, see e.g. [14] which indicates 33, which fits the Nord 2000 data quite good.

At 70 km/h, which is the reference speed in the Harmonoise project, [2], the difference between the Swedish measurements and the Danish measurements is 1,9 dB, whereas the mean difference is 1,7 dB. The figure, which shows the speed range 35-110 km/h, is based on 2452 Danish measurements and 710 Swedish measurements. A comparison with

117 Norwegian measurements from the same time indicates a corresponding difference of 0,8 dB.

The Danish measurements have been carried out with an average temperature of 13ºC and a typical road surface is DAC 0/12. Most of the Swedish measurement have been taken on SMA 0/16 and around 15º. According to the basic Harmonoise model with corrections for DAC/SMA, chip size and temperature, the difference between the Swedish and Danish results should be 1,5 dB which is in quite good agreement with the measured values. The Harmonoise values have been calculated using the Danish conditions

4.2 Category 2 vehicles

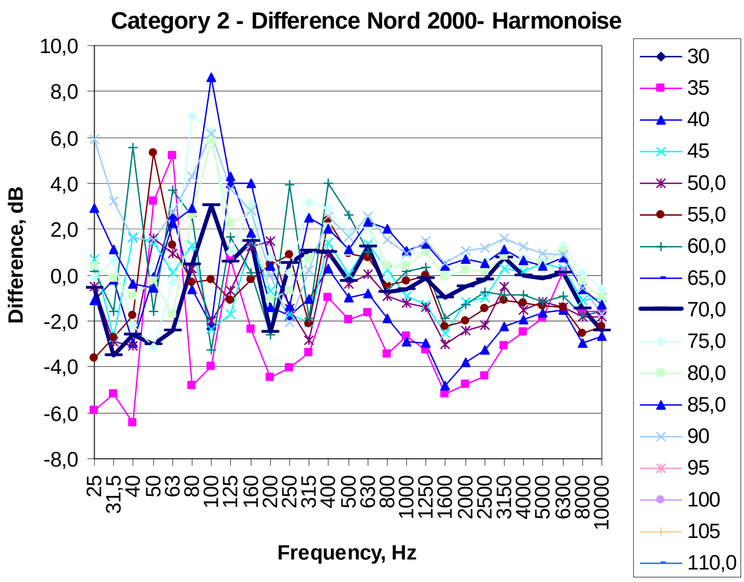


Figure 4.4 Mean difference in L_{EA} =- 0,2 dB, s= 1,4 dB. 30, 65, and > 90 km/h have been excluded due to too few samples (< 22)

4.3 Category 3 vehicles

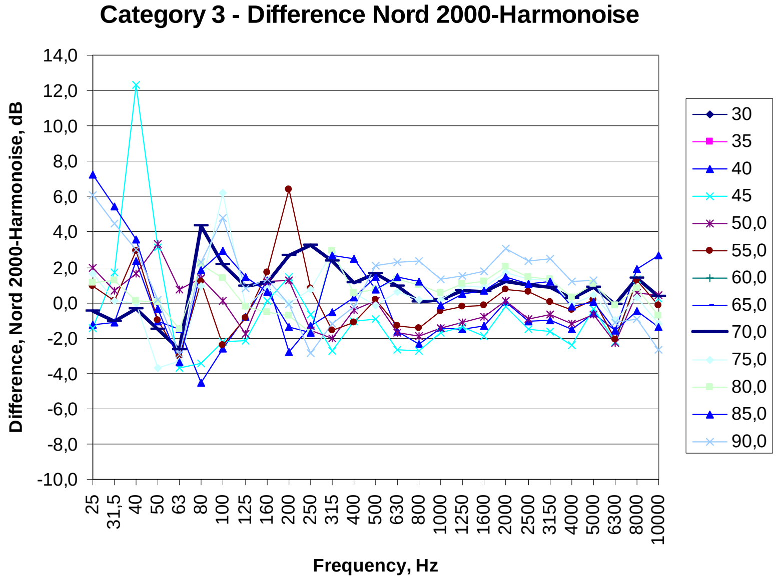


Figure 4.6 Mean difference in L_{EA} = 0,2 dB, s= 1,1 dB. 30, 35, 60 and 65 km/h have been excluded due to too few samples (< 25)

4.4 Discussion

It is obvious that the Harmonoise speed coefficients are not suitable for use in the Nordic countries. In order to get a good fit to available data they will have to be changed.

5 Adaptation of Harmonoise to Danish data

5.1 Introduction

Based on the results discussed in clause 4 the sound power coefficients of the Harmonoise source model were changed to fit the Danish Nord 2000 as well as possible. In the following the new result will be called DK Nord 2005. The starting point was to change the speed coefficients (b_R) to yield the right speed dependence. This was quite simple for category 1 vehicles as tyre/road noise dominates strongly. After that the other coefficients were fitted. As in Harmonoise Category 2 and 3 vehicles were given the same speed coefficients as Category 1 vehicles. The resulting coefficients are given in Annex A. The results are summarized in 5.2 and frequency band data are given in 5.3.

When doing this fitting the Harmonoise point source model was used together with the calculated transfer functions from each point source to the receiver at 4 m height at a distance of 9,2 m from the nearest wheel. The road surface was assumed to have an impedance corresponding to a specific flow resistivity of 200 MPas/m^2. The transfer functions were calculated using the Nord 2000 propagation model.

5.2 Summary of final result

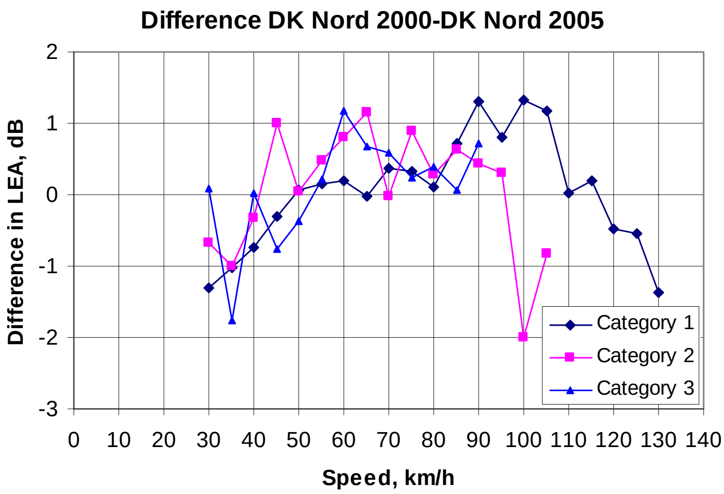


Figure 5.1 Difference between Nord 2000 and the revised Harmonoise (DK Nord 2005)

Table 5.1 Figure 5.1 in figures.

	Category 1	Category 2	Category 3
Mean	0,0	0,1	0,1
Stdev	0,8	0,9	0,7

5.3 Results in frequency bands

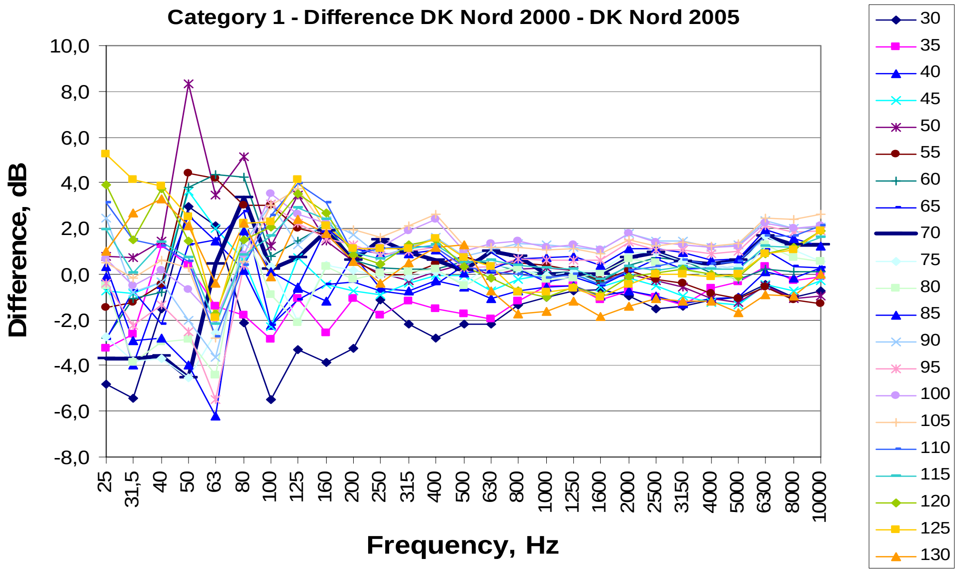


Figure 5.2 Comparison with measured Danish data and a revised Harmonoise source model (DK Nord 2005). Mean difference in L_{EA} = 0,0 dB, s= 0,8 dB

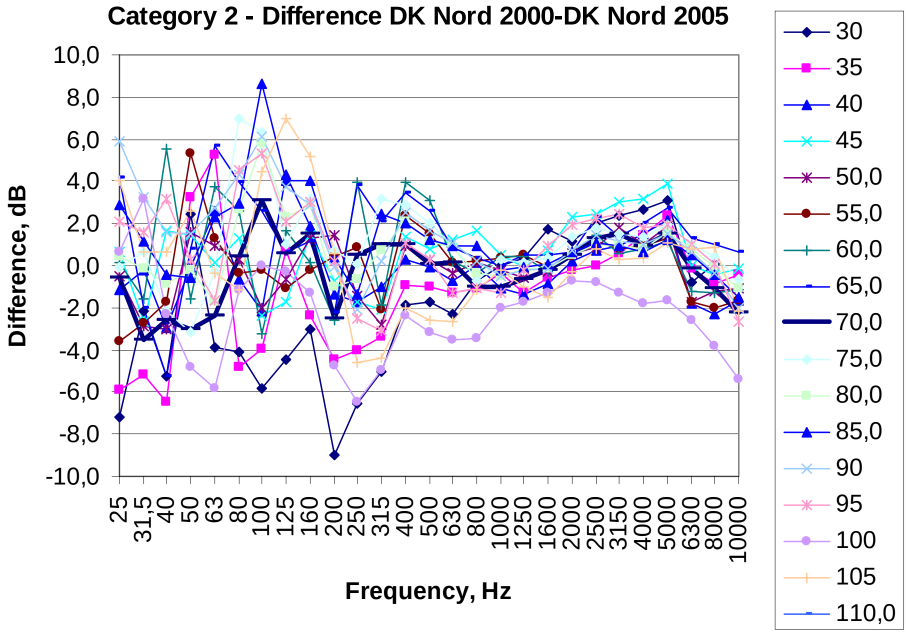


Figure 5.3 Mean difference in L_{EA} 0,1 dB, s= 0,9 dB. 30, 65, and > 90 km/h have rather few samples (< 22)

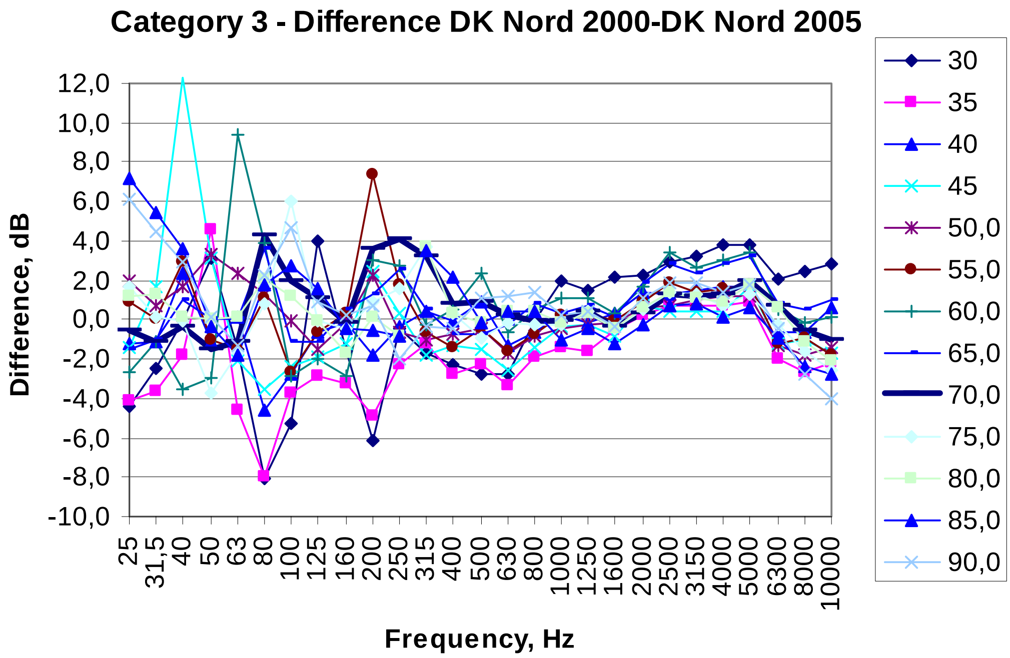


Figure 5.4 Mean difference in L_{EA} = 0,1 dB, s= 0,7 dB. 30, 35, 60 and 65 km/h have rather few samples (< 25)

6 Adaptation to Swedish data

6.1 Comparison between Swedish data and DK Nord 2005

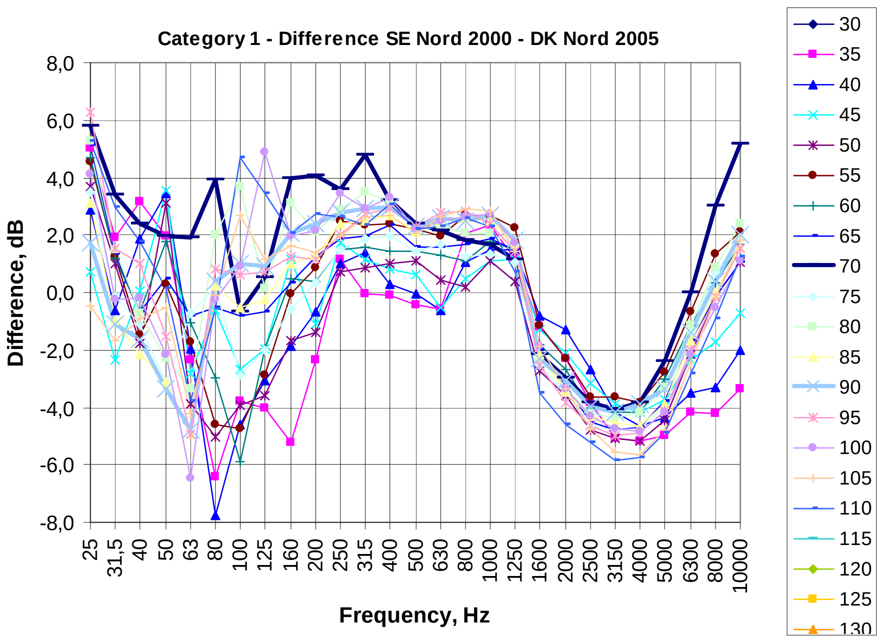


Figure 6.1 Comparison between the Swedish Nord 2000 data and the revised Harmonoise (DK Nord 2005). For A-weighted sound exposure levels the average difference is 0,0 dB with the standard deviation 0,4 dB.

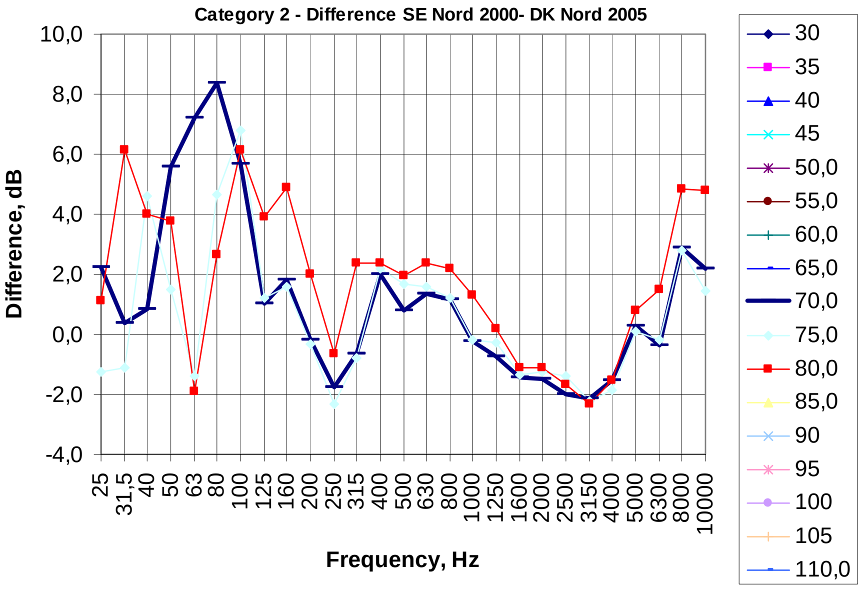


Figure 6.2 Comparison between the Swedish Nord 2000 data for category 2 and the revised Harmonoise (DK Nord 2005). For A-weighted sound exposure levels the average difference is 0,3 dB with the standard deviation 0,5 dB.

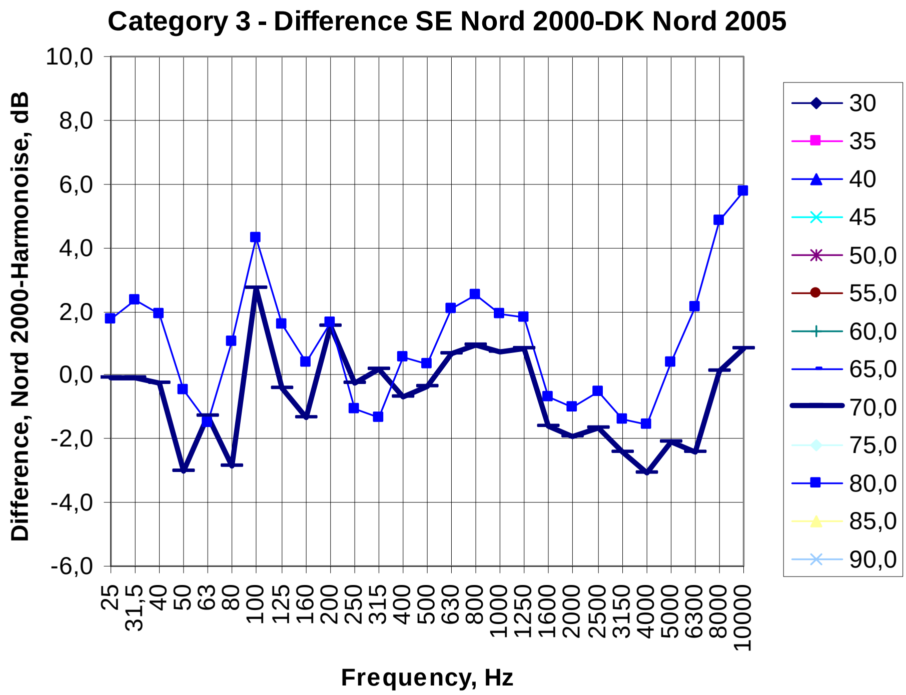


Figure 6.3 Comparison between the Swedish Nord 2000 data for category 3C+3D and the revised Harmonoise (DK Nord 2005). For A-weighted sound exposure levels the average difference is 0,6 dB.

Figure 6.1-6.3 indicate clearly that the agreement between the Swedish Nord 2000 data and the revised DK-adapted Harmonoise model is excellent as far as A-weighted values are concerned. This means that the Harmonoise model succeeds in correcting the earlier difference between Danish and Swedish data thanks to the 1,6 dB difference between SMA 0/16 and DAC 0/12. However, the results also clearly indicate that there are systematic differences if we study the frequency bands. The DK Nord 2005 model overestimates the sound pressure level around 4000 Hz and underestimates it around 1000 Hz. This systematic trend can also be seen in new measurements taken in Sweden during 2005. Some examples are shown in figure 6.4 and 6.5.

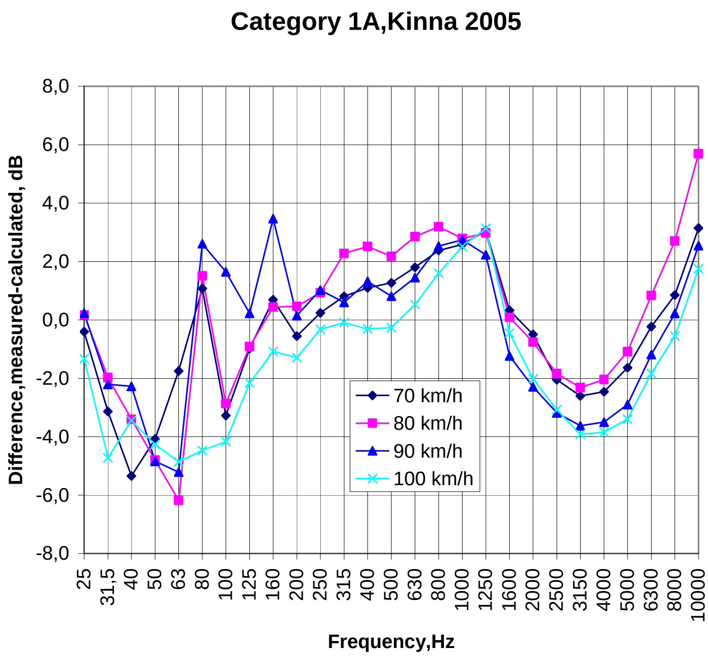


Figure 6.4 Difference between new Swedish measurements and the revised Harmonoise (DK Nord 2005)

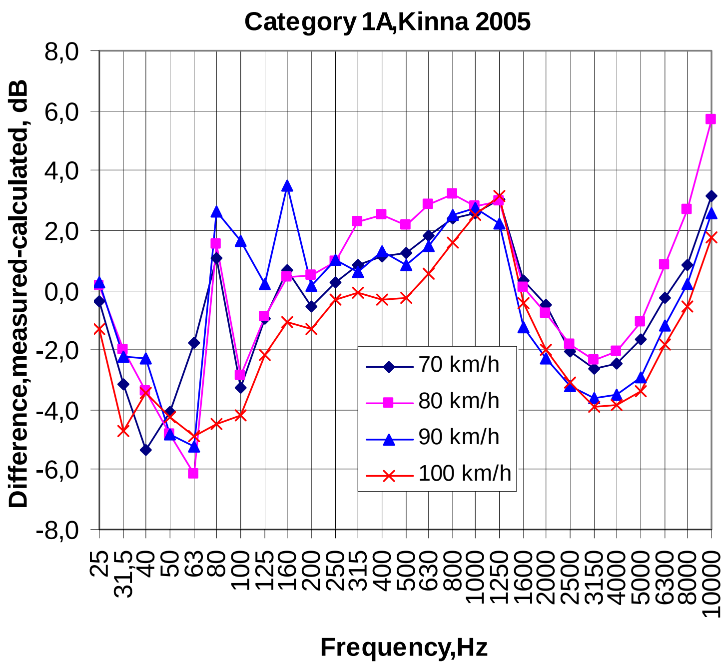


Figure 6.5 Difference between new Swedish measurements and the revised Harmonoise (DK Nord 2005)

The explanation of this systematic difference between Danish and Swedish data is not known. However, a reasonable hypothesis is that it is mainly due to the difference in road surfaces and in particular to the extensive use of studded tyres in Sweden, which tend to roughen the road surfaces. Thus it seems reasonable to adjust the coefficient a_R for tyre/road noise.

6.2 Correction of DK Nord 2005 coefficients

In order to correct for the difference discussed in 6.1 the corrections given in table 6.1 have been applied to the coefficients of DK Nord 2005. These corrections are the same for all categories of vehicles. According to most sources in literature the corrections should be smaller for heavy vehicles. However, as the corrections seem to be a step in the right direction also for these we have kept them for all categories. The solution given is a compromise between the Swedish Nord 2000 measurements and some of the recent measurements carried out during 2005.

Table 6.1 Corrections applied to the tyre/road coefficient a.

Frequency	250	315	400	500	630	800	1000	1250	1600	2000	2500	3150	4000	5000	6300	8000	10k
Correction	1,0	1,0	1,0	1,0	2,0	2,0	2,0	2,0	-1,0	-2,0	-3,0	-4,0	-4,0	-3,0	-1,0	0,0	2,0

The results obtained using the corrections in table 6.1 are reported in clause 6.3 for A-weighted levels and in clause 6.4 for 1/3-octave band levels.

6.3 Summary of Swedish results

The Swedish Nord 2000 measurements have been compared with results calculated using the Nord 2005 DK model with corrections according to table 6.1 and a summary of the results is shown in Figure 6.6. The agreement is good. On average there is a small overestimate of the calculated sound exposure levels. This overestimate is only a few tenths of a dB and it corresponds roughly to the difference between a road impedance of 200 MPas/m^2 and one of 20 MPas/m^2. This difference will disappear if the default impedance is changed from 200 MPas/m^2 to 20 MPas/m^2.

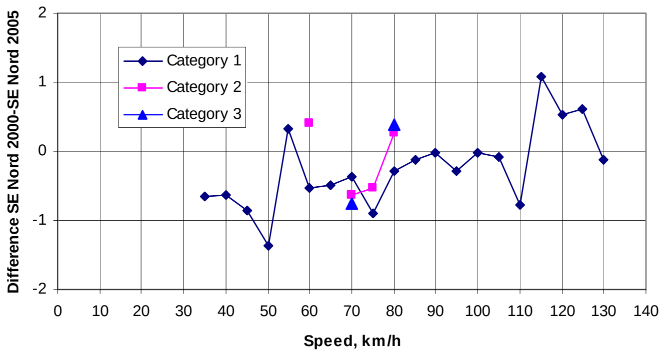


Figure 6.6 Difference in A-weighted sound exposure levels during pass-by between Swedish Nord 2000 measurements and the revised DK Nord 2005 (SE Nord 2005)

Table 6.2 Figure 6.6 in figures.

	Category 1	Category 2	Category 3
Mean	-0,3	-0,1	-0,2
Stdev	0,6	0,5	

6.4 Results in frequency bands

6.4.1 Comparison with SE Nord 2000 data

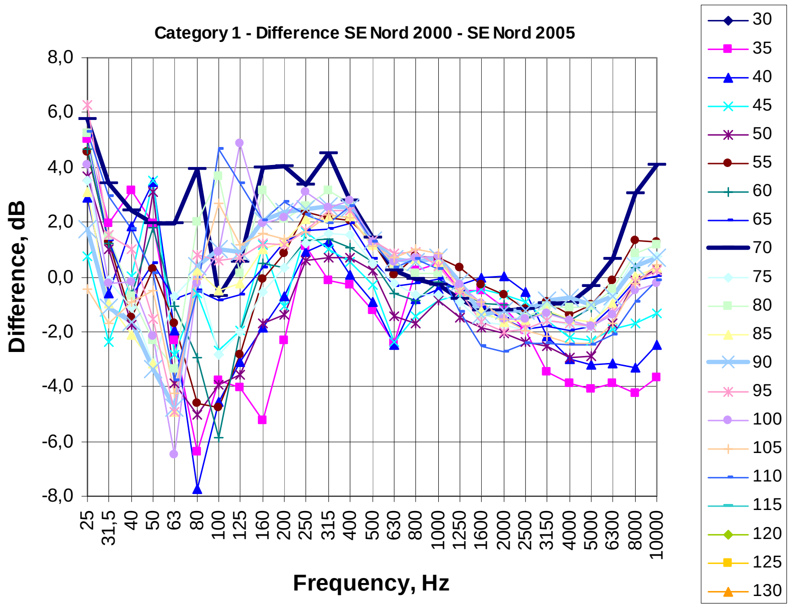


Figure 6.7 Difference in sound exposure levels between Swedish Nord 2000 measurements and SE Nord 2005

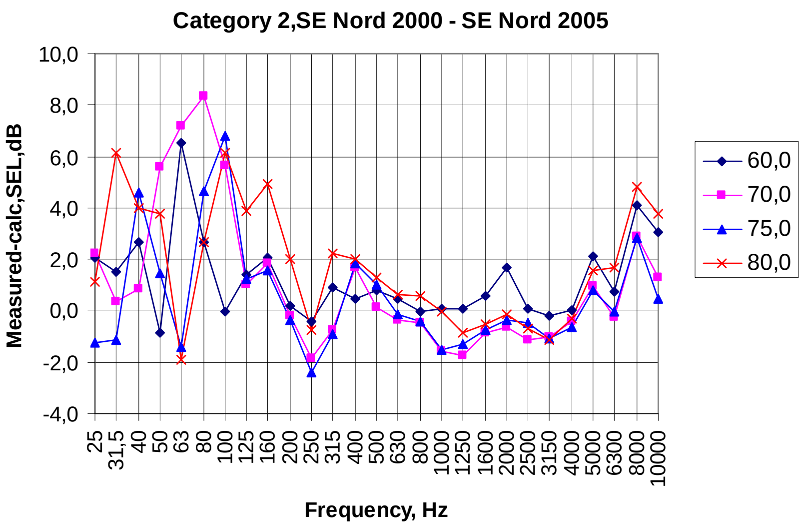


Figure 6.8 Difference between Swedish Nord 2000 measurements and SE Nord 2005

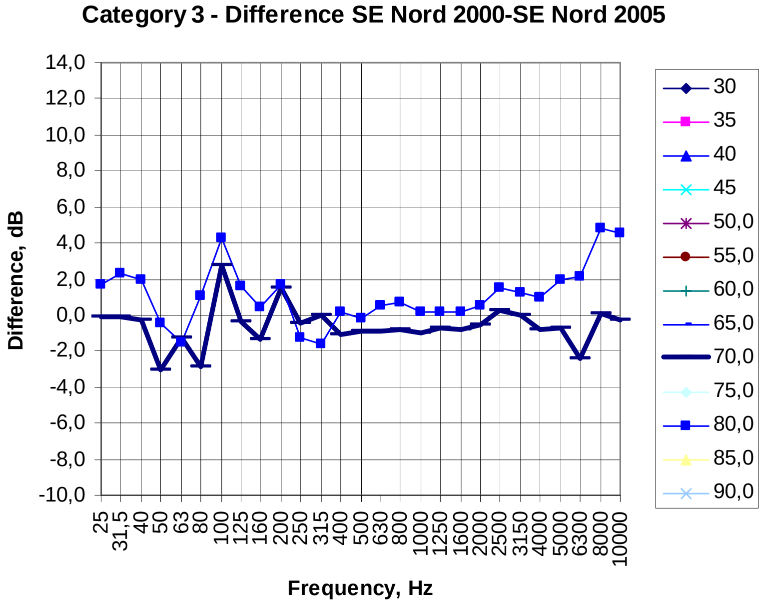


Figure 6.9 Difference between Swedish Nord 2000 measurements and SE Nord 2005

6.4.2 Comparison with some other Swedish data

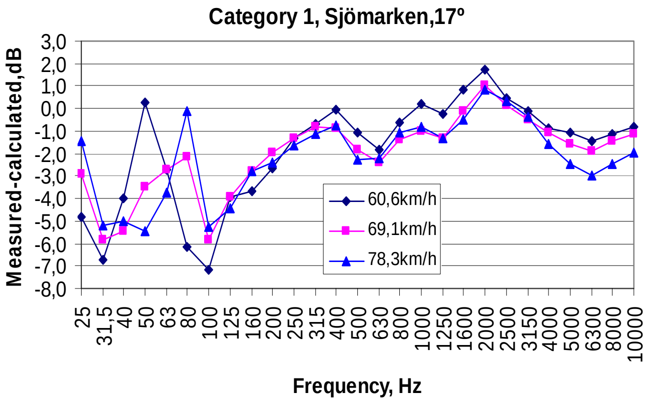


Figure 6.10 Difference between new(2005) Swedish measurements and SE Nord 2005

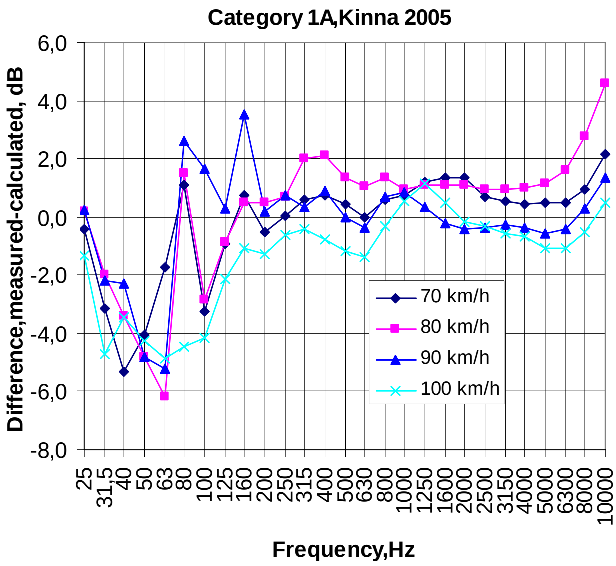


Figure 6.11 Difference between new(2005) Swedish measurements and SE Nord 2005

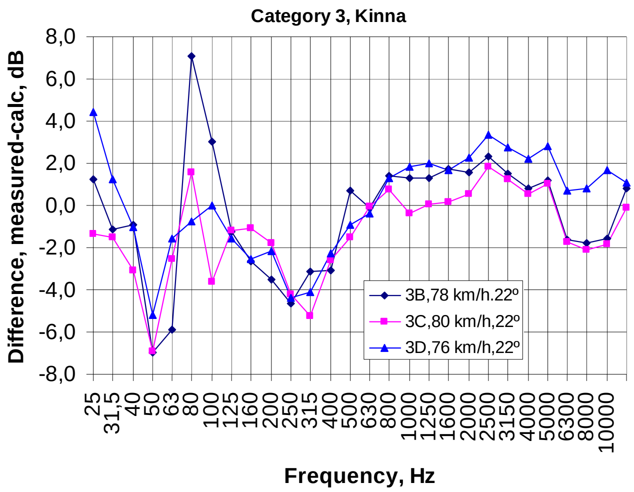


Figure 6.12 Difference between new(2005) Swedish measurements and SE Nord 2005

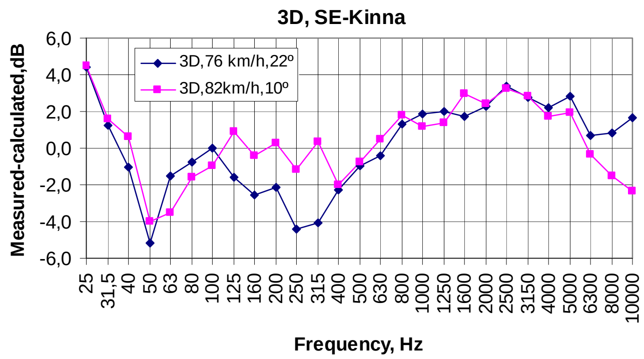


Figure 6.13 Difference between new(2005) Swedish measurements and SE Nord 2005

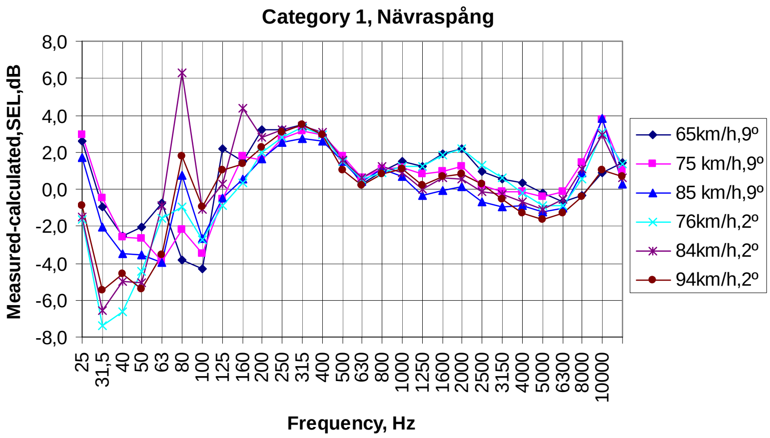


Figure 6.14 Difference between new(2005) Swedish measurements and SE Nord 2005

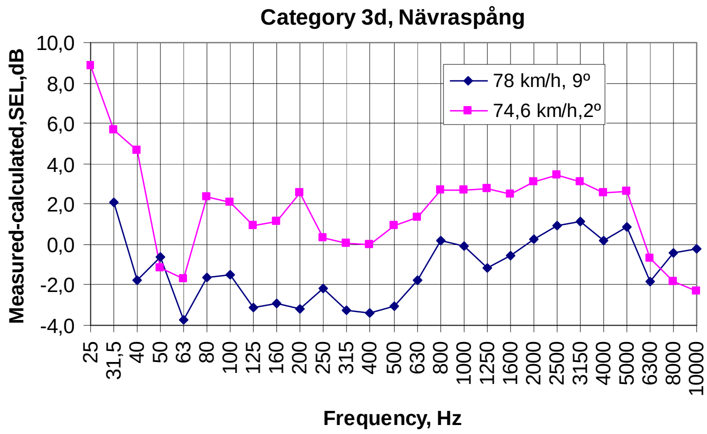


Figure 6.15 Difference between new(2005) Swedish measurements and SE Nord 2005)

In Figure 6.16 a comparison is made between measured coasting levels on 4 different Volvo trucks and levels calculated using the SE Nord 2005 modified Harmonoise model. The agreement is rather good above 315 Hz. For lower frequencies the discrepancy is significant, probably because of transmission noise that is not included in the Harmonoise model.

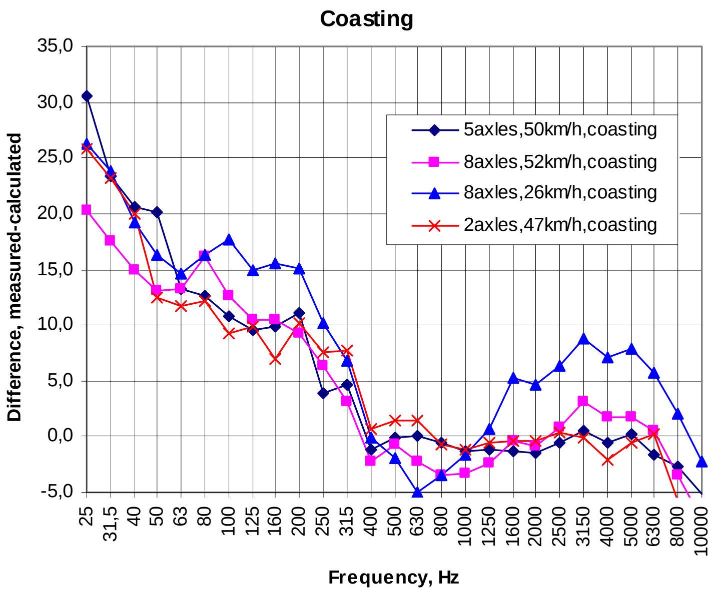


Figure 6.16 Comparison between measured coasting levels and calculated levels using the revised Harmonoise SE Nord 2005 model, from [11].

7 Other Nordic data

7.1 Finnish measurements

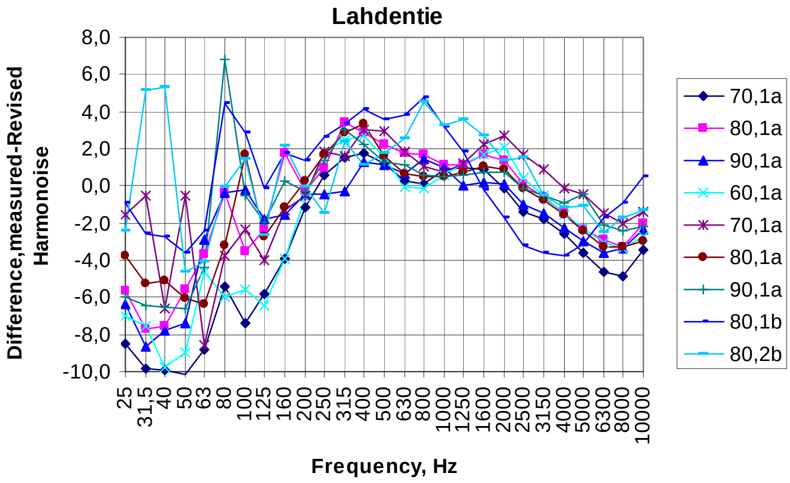


Figure 7.1 Difference between some Finnish measurements and SE Nord 2005.

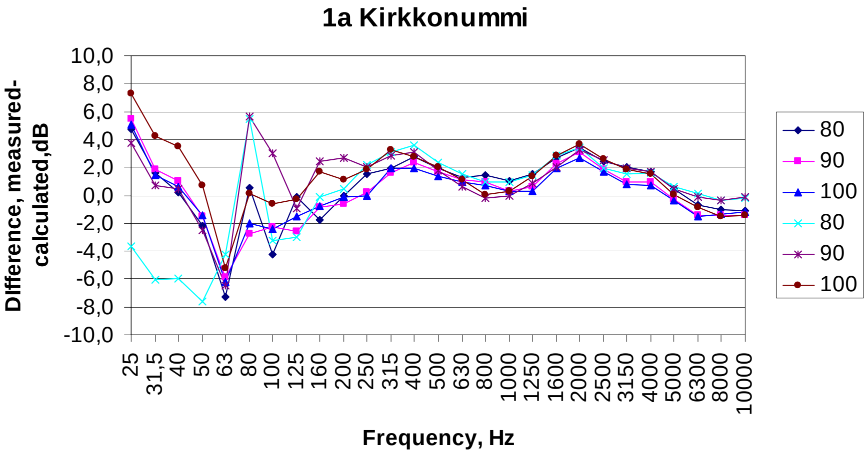


Figure 7.2 Difference between some Finnish measurements and SE Nord 2005.

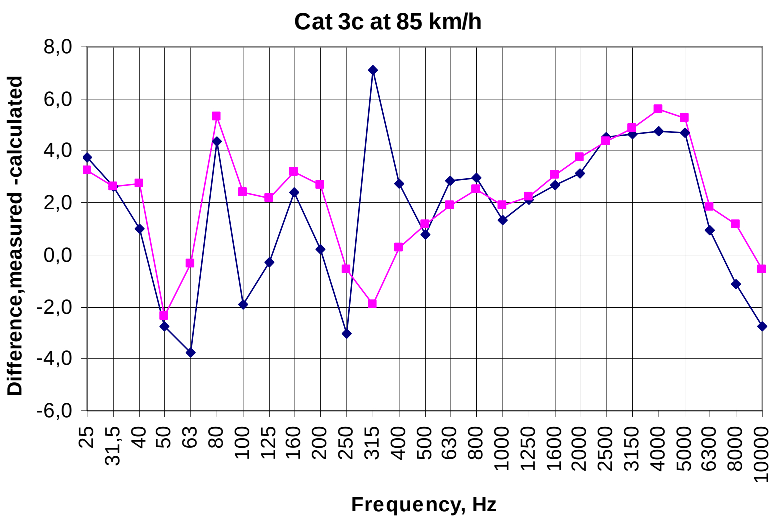


Figure 7.3 Difference between some Finnish measurements and SE Nord 2005.

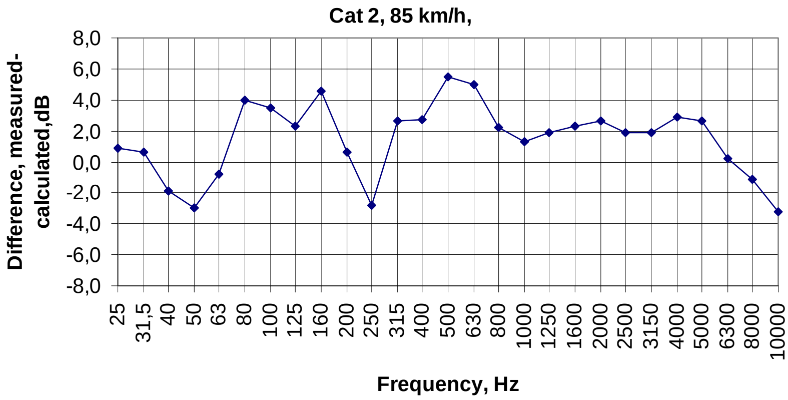


Figure 7.4 Difference between some Finnish measurements and SE Nord 2005.

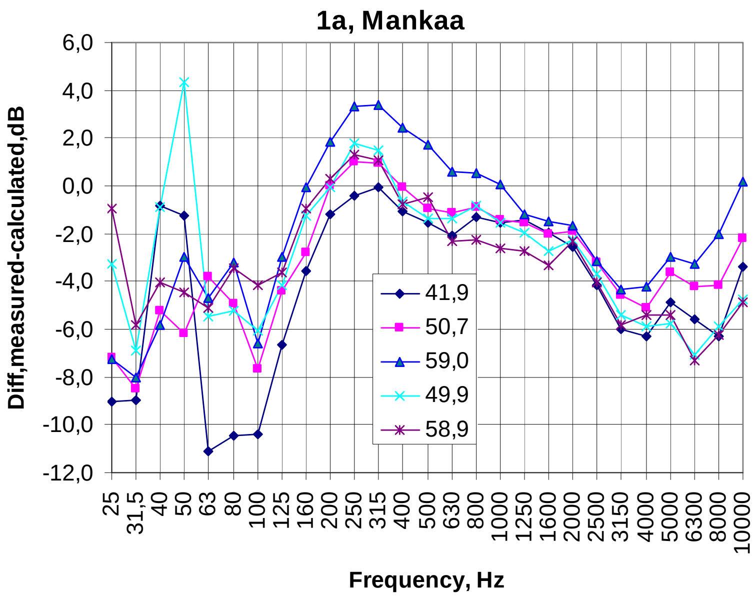


Figure 7.5 Difference between some Finnish measurements and SE Nord 2005.

7.2 Norwegian measurements

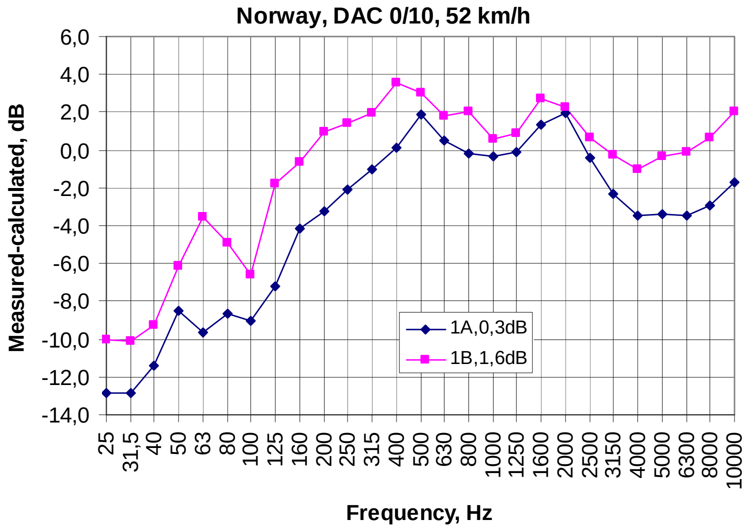


Figure 7.6 Difference between some Norwegian measurements and SE Nord 2005.

7.3 Conclusions

The Finnish data seem rather consistent with the Swedish data for category 1 vehicles. For category 2 and 3 the data available is rather small. There are some indications that the measured levels are higher but it is dangerous to draw any conclusions from the limited data set. For the time being it seems reasonable to apply the same coefficients as for Sweden.

8 Other corrections

8.1 Studded tyres

In Harmonoise the correction is given as $a + b$ lg(v). Some new results indicate that the influence is smaller than given by Harmonoise. Using the results of figure 8.1 new coefficients have been derived. They are given in table A.3 in annex A adapted to the following equation

$$\begin{aligned} &\Delta L_{studs}(v) = a + b \cdot \lg\left(\frac{v}{70}\right), \; 50 \le v \le 90 \;\text{ km/h} \\ &\Delta L_{studs}(v < 50) = \Delta L_{studs}(50) \\ &\Delta L_{studs}(v > 90) = \Delta L_{studs}(90) \end{aligned} \tag{8.1}$$

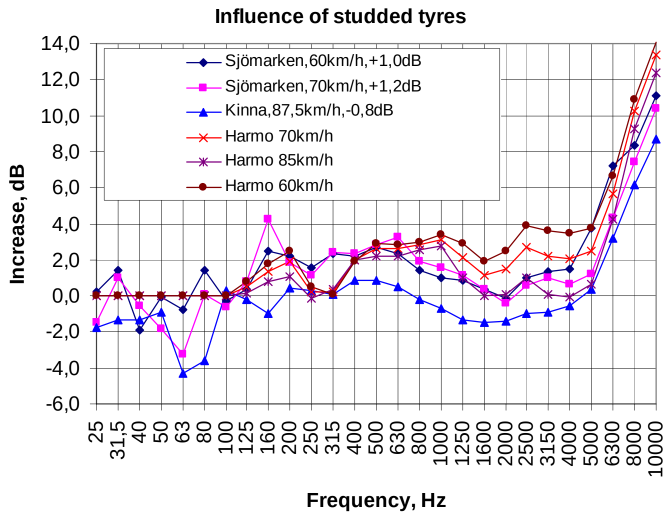


Figure 8.1 Influence of studded tyres. Comparison between the Harmonoise model and some new measurements

8.2 Temperature

The Harmonoise source model has a very simple temperature correction. For DAC and SMA surfaces it is 0,1 and 0,06 dB/º respectively. These corrections have been checked at two locations in Sweden and the results are shown in figure 8.2 and 8.3. As can be seen the agreement is quite good. For figure 8.2 and 8.3 Harmonoise yields 0,7 dB and 0,7 dB respectively compared to the measured values 0,8 dB, 0,5 dB and 1,1 dB respectively.

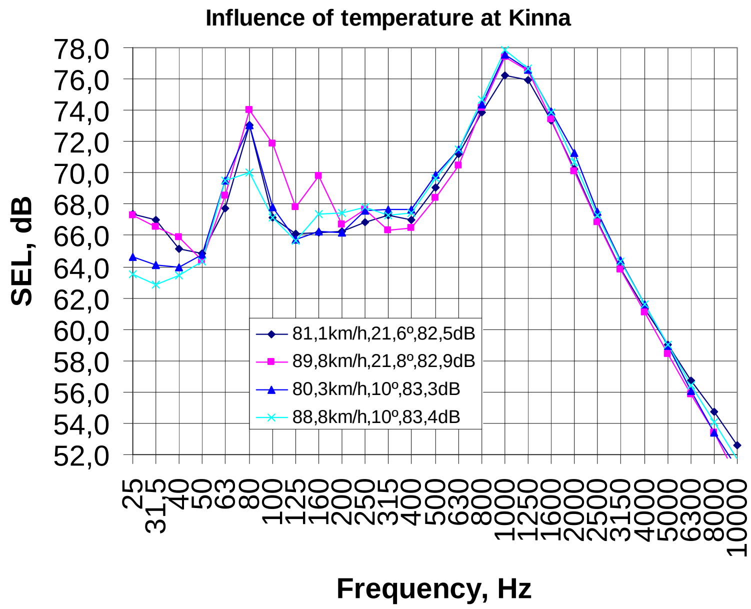


Figure 8.2 Influence of temperature. Measurements at the same place at different temperatures. SMA road surface.

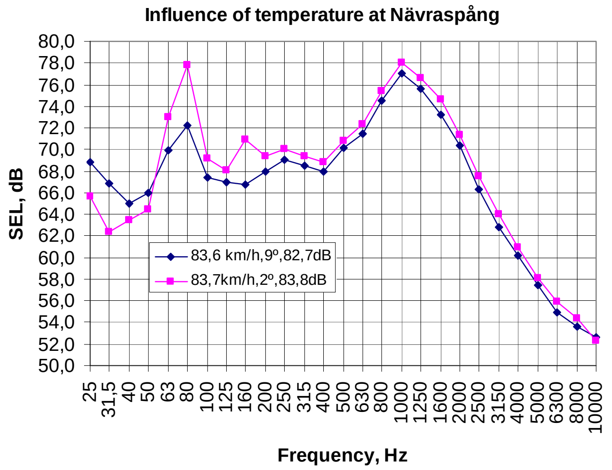


Figure 8.3 Influence of temperature. Measurements at the same place at different temperatures. DAC road surface.

8.3 Other road surfaces

In clause 2.3.3 the most common road surfaces within the reference cluster is taken into account. For other road surfaces it is difficult to make general corrections. Nominally the same road may have different properties depending on where and when it was constructed. Thus it is recommended to determine the correction in each individual case. This is most simply done by carrying out pass-by tests and then compare with a measured or calculated reference surface. Preferably the tests are carried out according to the methods proposed within the European SILVIA project. The difference can then be stated like

$\Delta L_{\text{surface}}$ = 2 dB rel. reference road surface (Average of DAC 0/11 and SMA 0/11)

This difference is often different for light and heavy vehicles. $\Delta L_{\text{surface}}$ can either be given for each one third octave band or for the A-weighted value. If only the A-weighted correction is used it has to be applied equally for each frequency band. In [14] some examples on frequency independent $\Delta L_{\text{surface}}$ are given with DAC 0/11 as reference. A few examples are given in table 8.1. There are also some frequency dependent examples in [2]. The corrections apply to tyre/road noise only. It is also necessary to determine the temperature coefficient, which can either be measured or determined from table 2.1.

Table 8.1 Some examples of $\Delta L_{surface}$, from [14]

Road surface type	Identifyer	LDV	HDV
Asphalt concrete 0/11 (Reference)	*DAC 0/11*	*0,0*	*0,0*
Drainage asphalt 0/08, less than 3 years	PAC 0/8	-5,8	-3,7
Drainage asphalt 0/11, less than 3 years	PAC 0/11	-3,1	-3,7
Drainage asphalt 0/16, less than 3 years	PAC 0/16	-2,0	-3,0
Cement concrete, logitudinally brushed	CCB lo	1,3	1,7
Cement concrete, transversely brushed	CCB tr	3,7	2,1
Even pavement stones	PS even	3,0	2,0
Uneven pavement stones	PS uneven	6,0	4,0

For porous surfaces it is important to take the deterioration over time into account. Newly laid surfaces are in general quieter than older ones. For surfaces within the refernce cluster the deterioration becomes stable already after 2 years. However, if the surface is porous then the deterioriation continues for 7 years. For porous surfaces like PAC, PCC, PERS and OGAC the equation is

$$\Delta L_T = \Delta L_0 (1 - (0{,}25T - 0{,}016T^2)), T \leq 7\, years \quad (8.2)$$

where ΔL_0 is the sound pressure level for the individual frequency band relative the reference surface at the time T=0 years. The correction is made at each band frequency for the rolling noise component.

9 Selection of speed and acceleration

9.1 Freely moving traffic

Within the Harmonoise some studies were carried out to investigate the effect of speed variations of a traffic flow, [10]. It was concluded that L_{Aeq} was underestimated only by a few tenths of a dB by using the average speed in stead of considering the speed distribution. The conclusion is that the average speed for each vehicle category is sufficient to describe the situation under free flow conditions.

9.2 Crossings and roundabouts

In [8] it was shown that, for category 1 vehicles, crossings and roundabouts slow down the speed of vehicles and that this slow down causes the sound power level to decrease. The acceleration, if any, will have limited influence for light vehicles. For a speed limit of 50 km/h the sound exposure level in roundabouts corresponded to a speed of about 30 km/h.

For heavy vehicles the situation is a little different as the noise emission very much is influenced by the acceleration. Figure 9.1 clearly indicates that acceleration from complete stand still increases the sound exposure level and that this increase is not very sensitive to the speed. In the vicinity of a roundabout or corner the sound exposure level is less than during this free acceleration. Unless the vehicle stops completely the SEL-levels are about the same as that for the vehicle cruising at 30 km/h. This behaviour is similar to that of cars. However, if the vehicle comes to a complete stop SEL increases and comes closer to the level of cruising at 50 km/h. After the crossing/roundabout the truck will have to accelerate up to cruising speed and then the sound power level has to increase accordingly during a distance of 50-200 m as is indicated by the results from the 5 microphone positions.

A possible practical solution to be used for engineering calculations could be: For heavy vehicles in urban traffic use the speed 30 km/h in and in the vicinity of roundabouts and crossings without traffic light and with a low traffic flow. In case of traffic lights or if the flow increases the vehicle will often have to stop and in that case the use of 50 km/h would be more appropriate. As an alternative for this case we can use the real speed which is close to 30 km/h and then correct for acceleration (0,5 m/s^2 corresponds to an increase of about 3 dB for propulsion noise) according to the Harmonoise acceleration model 100 m before and after each roundabout/crossing.

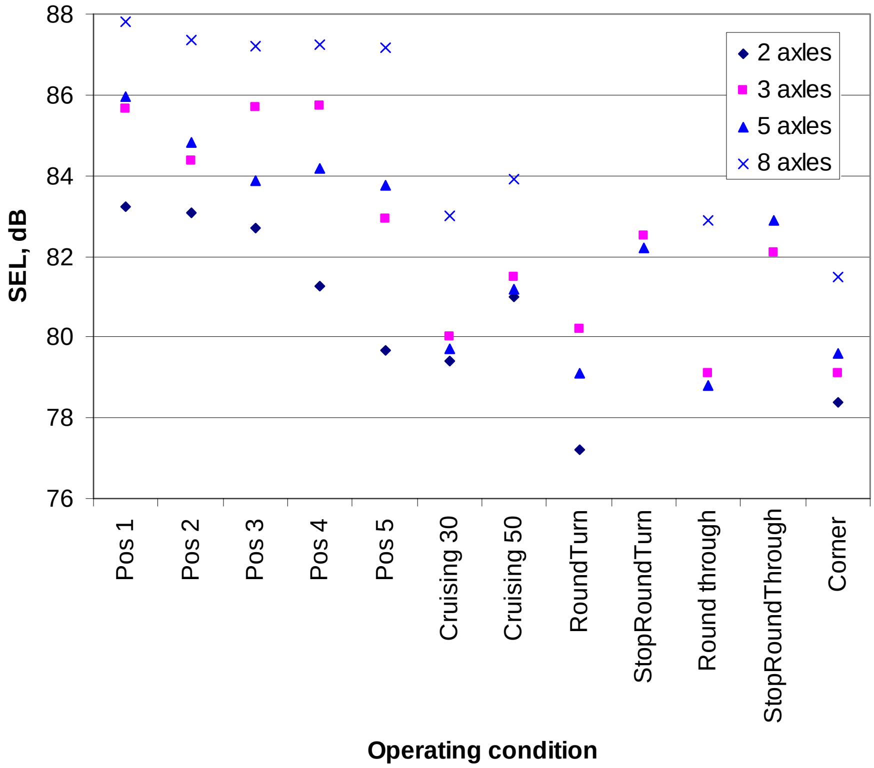


Figure 9.1 Effect of acceleration on SEL from heavy vehicles.

Figure 9.1 can also be used to veryfy the harmonoise acceleration model. In table 9.1 the measured differences between acceleration and crusing are compared with the same differences calculated using the SE Nord 2005 model. We can see that the agreement is quite good.

Table 9.1 Analysis of the measurements in figure 9.1.

	5 axles	8 axles
Average acceleration	0,65 m/s^2	1,2 m/s^2
Microphone at 30 km/h	M3	M2
Microphone at 50 km/h	--	M5
Measured SEL at M3-SEL at cruising 30km/h Calculated	4,3 dB 3,0 dB	
Measured SEL at M2 - SEL at cruising 30 km/h Calculated		4,5 dB 5,4 dB
Measured SEL at M5 - SEL at cruising 50 km/h Calculated		3,4 dB 3,8 dB

9.3 Road gradients

Volvo, [7] has simulated cases in a test rig and these results indicate that the Harmonoise correction for acceleration works reasonably good. According to Volvo the noise increases with 0,3 dBA/% road grade in the powertrain rig and 1,0 dBA/% road grade in the truck noise chamber. In the Harmonoise model it is assumed that a slope corresponds to an acceleration equivalent to the component of the gravitational force that is

$$a = g \cdot \sin(angleofslope) \approx 10 \cdot \text{slopein\%}/100 \qquad (9.1)$$

which, according to eq. (4.1) corresponds to an increased noise level of

$$\Delta L = 5{,}6 \cdot a = 5{,}6 \cdot slope\% / 10 \qquad (9.2)$$

This corresponds to 0,6 dB per % road grade, which is a surprisingly good average of the above figures 0,3 and 1,0 dB respectively.

10 Default values for road impedances

In order to be able to make correct sound propagation calculations the acoustic impedance of the road surface has to be known. Recommended default values are given in table 10.1.

Table 10.1 Road impedances to use

Type of road	**Flow resistivity**	**Reference**
Very hard road surface	200 MPas/m^2	[15]
Normal road	20 MPas/m^2	[15]
ISO surface	2 MPas/m^2	[2]
Gravel road[1)]	2 MPas/m^2	[16]
Porous road	Hamet impedance model	[2]

[1)] The coefficients given in Annex A to determine the sound power levels are not valid for this case.

11 Algorithm for point source integration

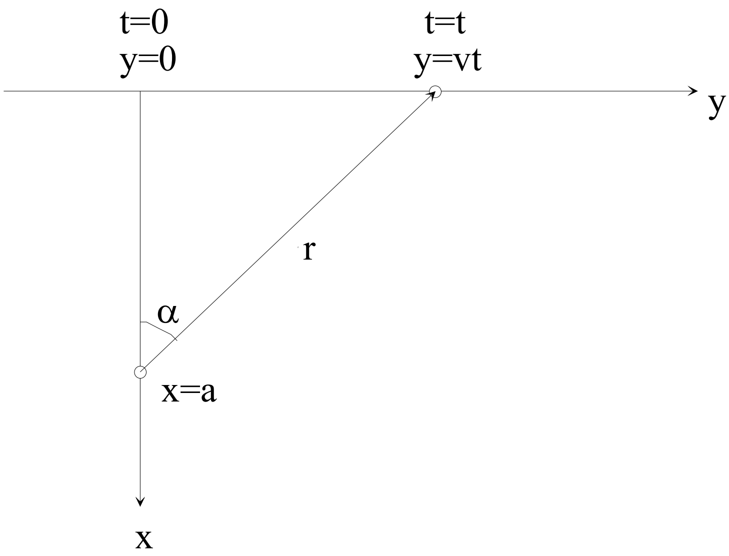


Figure 11.1 Geometry of the pass-by of a point source.

Large scale mapping programs usually use about one ray/degree for each propagation calculation. In such cases any numerical integration will perform very well. However, in case of single point semi manual calculations much time can be saved by reducing the number of propagation paths for the calculations.

The sound exposure level, L_E, due to a point source with the sound power W passing by is, for the time interval t_2-t_1, given by

$$L_E = 10\lg\int_{t_1}^{t_2} \frac{p^2(t)}{p_0^2}dt \tag{11.1}$$

The corresponding L_{eq} level for any time T is given by

$$L_{eq} = L_E - 10\lg(T) \tag{11.2}$$

where

$$\frac{p^2(t)}{p_0^2} = \frac{W(t)}{W_0 \cdot 4\pi \cdot r^2(t)} \cdot \delta(t) \tag{11.3}$$

where

δ(t) is an attenuation/amplification function taken the effect of ground reflections, air attenuation, etc. into account. W is a function of t as it has some horizontal directivity. The distance $r(t)$ between the receiver at $x= a$ and the source is given by

$$r(t) = \sqrt{v^2t^2 + a^2 + (h_r - h_s)^2} \tag{11.4}$$

where v is the speed (m/s) of the point source. Combining these equations yields

$$L_E = L_W - 10\lg(4\pi) + 10\lg\left[\int_{t_1}^{t_2} \frac{\delta(t)\cdot\Delta W(t)}{v^2t^2 + a^2 + (h_r - h_s)^2}dt\right] \tag{11.5}$$

where L_W is the equivalent omni-directional sound power level and ΔW the correction due to directivity.

The task is to integrate eq. (11.5) in the most efficient way. The problem is that $\delta(t)$ will be calculated with a rather complicated propagation model and that it will vary with time (which can be transformed into distance) and changes in terrain topography. Thus the integration of (11.5) will have to be discretized in intervals small enough to allow for approximately constant values for 10 lg(δ) within each interval or, alternatively selecting a value of δ representative for the interval. In the old Nordic model only one angle interval was used and δ of the bisector of the segment was used. If we choose a segment small enough the condition $\delta(t)$= constant and ΔW(t)= constant will always be fulfilled. In that case the substitution $vt/\sqrt{a^2 + (h_r - h_s)^2}$ = arctan(α) allows for an analytical integration yielding

$$L_E = L_W + 10\lg(\sqrt{a^2 + (h_r - h_s)^2}) - 10\lg(v) - 10\lg(4\pi(a^2 + (h_r - h_s)^2) + 10\lg(\Delta\alpha\cdot\delta\cdot\Delta W(\alpha = \frac{\alpha_2 - \alpha_1}{2})) \tag{11.6}$$

where

$$\Delta\alpha = \alpha_2 - \alpha_1 \tag{11.7}$$

and α_1 and α_2 are the angles associated with the times t_1 and t_2 respectively.

In [6] the proposal shown in table 11.1 is given. Each side of the normal has to be integrated independently unless the segments are symmetric on both sides as to both size and geometry.

Table 11.1 Proposal for number of segments to use for integration of point source contributions

	0-45°	45-85°	Total number 0-85°
Barriers	1	1/10° up to 65° and then 1/5°	7
Flat/omnidirectional	1	1	2
Flat/directional	1	2	3

According to table 11.1 we need as a minimum 3 segments to integrate 90° for a directional source. Thus an example of a flexible adaptation is the following:

If α_1, $\alpha_2 < 45°$ calculate and use δ and ΔW for $(\alpha_2-\alpha_1)/2$.

If $\alpha_2 > 45°$ calculate δ for $\alpha = 45°$ and $\alpha = \alpha_2$. If $\delta_{\alpha 2}-\delta_{45°} \leq 3$ dB use $\delta = (\delta_{\alpha 2}-\delta_{45°})/2$ for the remaining segment. If $\delta_{\alpha 2}-\delta_{45°} > 3$ dB then calculate δ for $\alpha = (\alpha_2-45°)/2$ and then proceed as last step until the difference becomes less than 3 dB between two nearby angles.

If the contributions from stationary vehicles are to be included they should be calculated using a time integration according to the original Nord 2000 method.

12 References

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[5] Ulf Sandberg & Jerzy Ejsmont, Tyre/road reference book, Informex 2002

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[14] P.A. Morgan, P.M. Nelson & H. Steven, Integrated assessment of noise reduction measures in the road transport sector, PR SE/652/03, ETD/FIF.20020051 from TRL & RWTüV

[15] Hans Jonasson & Svein Storeheier, Revision of NT ACOU 104 for the Measurement of the Acoustic Impedance of Ground, Nordic Innovation Centre (NICe), project number 04145

[16] NT ACOU 104, Ground surfaces: Determination of the acoustic impedance

Annex A – Coefficients for sound power determination

$$L_{WR}(f) = a_R(f) + b_R(f)\lg\left[\frac{v}{v_{ref}}\right] \quad \text{(A.1)}$$

v_{ref}= 70 km/h. The coefficients $a_R(f)$ and $b_R(f)$ for each main vehicle category is given in table 6.3. For category 3 the tabulated values refer to 4 axles.

$$(a_R)_{Category3} = (a_R)_{Category2} + 10\lg\left(\frac{numberofaxles}{2}\right) \quad \text{(A.2)}$$

The propulsion noise is given by

$$L_{WP}(f) = a_P(f) + b_P(f)\left[\frac{v - v_{ref}}{v_{ref}}\right] \quad \text{(A.3)}$$

Table A.1 Basic sound power coefficients to use in Nord 2005 (See next page for corrections)

	Input version 051229rev											
Base coefficients to be used in DK Nord 2005							**Propulsion**					
			Cat. 2		Cat. 3 4 axles	4 axles	Category 1					
Rolling	Cat. 1								Category 2		Category 3	
	a_R	b_R	a_R	b_R	a_R	b_R	a_P	b_P	a_P	b_P	a_P	b_P
25	69,9	33	76,5	33,0	79,5	33,0	89,8	2	97	0	97,7	0
31,5	69,9	33	76,5	33,0	79,5	33,0	91,6	2	97,7	0	97,3	0
40	69,9	33	76,5	33,0	79,5	33,0	91,5	0	98,5	0	98,2	0
50	74,9	30	78,5	30,0	81,5	30,0	92,5	0	98,5	0	103,3	0
63	74,9	30	79,5	30,0	82,5	30,0	96,6	2	101,5	0	107,9	0
80	74,9	30	79,5	30,0	82,5	30,0	94,2	2	101,4	0	105,4	0
100	79,3	41	82,5	41,0	85,5	41,0	92	4	97	0	101	0
125	82,5	41,2	84,3	41,2	87,3	41,2	87,4	2	96,5	0	101	0
160	81,3	42,3	84,3	42,3	87,3	42,3	86,1	2	95,2	0	101,3	0
200	80,9	41,8	84,3	41,8	87,3	41,8	86,1	6	99,6	0	101,3	0
250	78,9	38,6	87,4	38,6	90,4	38,6	87,2	8,2	100,7	8,5	102,5	8,5
315	78,8	35,5	88,2	35,5	91,2	35,5	86,5	8,2	101	8,5	103	8,5
400	80,5	31,7	92	31,7	95,0	31,7	85,6	8,2	98,3	8,5	102	8,5
500	87,0	25,9	94,1	25,9	97,1	25,9	80,6	8,2	94,2	8,5	101,4	8,5
630	88,7	26,5	96,5	26,5	99,5	26,5	80,7	8,2	92,4	8,5	99,4	8,5
800	90,8	32,5	96,8	32,5	99,8	32,5	78,8	8,2	93,4	12,5	95,1	8,5
1000	93,3	37,7	95,6	37,7	98,6	37,7	79,3	8,2	95,5	12,5	95,8	8,5
1250	92,5	41,4	93	41,4	96,0	41,4	82,4	8,2	96	12,5	95,3	8,5
1600	92,8	41,6	93,9	41,6	96,9	41,6	83,7	8,2	93,8	12,5	92,2	8,5
2000	90,4	42,3	91,5	42,3	94,5	42,3	83,4	9,5	93,4	12,5	93,2	8,5
2500	88,4	38,9	88,1	38,9	91,1	38,9	81,3	9,5	92,1	12,5	90,7	8,5
3150	85,6	39,5	86,1	39,5	89,1	39,5	81,8	9,5	90,1	12,5	88,8	8,5
4000	82,7	39,6	84,2	39,6	87,2	39,6	79,9	9,5	87,9	12,5	87,5	8,5
5000	79,7	39,8	80,3	39,8	83,3	39,8	77,9	9,5	85,6	12,5	85,9	8,5
6300	75,6	40,2	77,3	40,2	80,3	40,2	75,1	9,5	85,7	8,5	86,9	8,5
8000	72,0	40,8	77,3	40,8	80,3	40,8	73,1	9,5	82,6	8,5	83,8	8,5
10000	67,5	41,0	77,3	41,0	80,3	41,0	69,5	9,5	79,5	8,5	80,3	8,5

For Swedish, Norwegian and Finnish roads the tyre/road (rolling) coeffients are to be corrected as given in table A.2

Table A.2 Corrections applied to the tyre/road coefficient a.

Frequency	250	315	400	500	630	800	1000	1250	1600	2000	2500	3150	4000	5000	6300	8000	10k
Correction	1,0	1,0	1,0	1,0	2,0	2,0	2,0	2,0	-1,0	-2,0	-3,0	-4,0	-4,0	-3,0	-1,0	0,0	2,0

For studded tyres the correction is given by

$$\Delta L_{studs}(v) = a + b \cdot \lg\left(\frac{v}{70}\right),\ 50 \le v \le 90\ \text{km/h}$$

$$\Delta L_{studs}(v < 50) = \Delta L_{studs}(50)$$

$$\Delta L_{studs}(v > 90) = \Delta L_{studs}(90)$$

where the coefficients are given by table A.3

Table A.3 Correction for studded tyres.

	Nord 2005	
	a	b
25	0,0	0
31,5	0,0	0
40	0,0	0
50	0,0	0
63	0,0	0
80	0,0	0
100	0,0	0
125	0,3	-4,1
160	1,4	-6,0
200	1,5	-8,5
250	0,9	-4,1
315	1,2	1,7
400	1,5	0,6
500	1,9	-4,6
630	1,8	-3,9
800	0,8	-2,7
1000	0,5	-4,2
1250	0,2	-11,7
1600	-0,2	-11,7
2000	-0,4	-14,9
2500	0,5	-17,6
3150	0,8	-21,8
4000	0,9	-21,6
5000	2,1	-19,2
6300	5,0	-14,6
8000	7,3	-9,9
10000	10,0	-10,2