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**Noise Emission of Heavy
Vehicles**

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Abstract

Measurements have been carried out in the laboratory and in the field to collect data to use to validate the Harmonoise source model for heavy vehicles. In general the results support the Harmonoise source model in all other aspects than the coefficients in the equations yielding the sound power level of propulsion and tyre/road noise. Nordic measurement results indicate that many of these coefficients need to be revised. New coefficients are proposed.

Different methods to separate propulsion and tyre/road noise are discussed and some measurements combined with a transfer matrix method indicate that the point source model of Harmonoise functions reasonably well.

Field measurements, which focused on simulation of urban driving, clearly show that acceleration has to be taken into account for heavy vehicles. The sound exposure level increases significantly during acceleration at low speeds and it is not possible to make accurate calculations for heavy vehicles in urban traffic without correcting for it. One way of doing this could be quite simply to add a default acceleration of approximately 0,5 m/s² for heavy vehicles in urban traffic.

For driving on roads with gradients the Volvo laboratory measurements support the simple Harmonoise model quite well at least if the gradient is small.

The results will be further developed and discussed in the European IMAGINE-project.

Key words: Noise emission, heavy vehicles, Harmonoise, measurements, acceleration

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Preface

This project has been supported by the Swedish EMFO research programme, project no. 310101736 with dnr AL90A 2004:15523. It has been carried out together with Volvo Truck Cooperation represented by Kaj Bodlund and Christina Keulemans.

1 Introduction

1.1 Background

The European Harmonoise project, see www.harmonoise.org, with participants from 19 different companies/institutions has developed a future harmonized prediction method for road and rail traffic noise. In the road traffic model the road vehicle is modelled as point sources on different heights above the road surface, [1]. The principles follow those of Nord 2000, [2], although the source heights are different. In contrast to Nord 2000 Harmonoise separates tyre/road noise and propulsion noise. Whereas Nord 2000 divides the total sound power equally between three equally strong sources Harmonoise distributes 80% of the tyre/road noise on a source 0,01 m above the ground and 20% either on 0,30 m or 0,75 m depending on the type of vehicle. For propulsion noise it is the other way around. Harmonoise supplies default values in terms of coefficients for equations for both tyre/road and propulsion noise.

The Harmonoise source model yields the sound power level of tyre/road (rolling noise), L_{WR} , and the sound power level of propulsion noise, L_{WP} given by the equations

$$L_{WR}(f) = a_R(f) + b_R(f) \lg \left[\frac{v}{v_{ref}} \right] \quad (1.1)$$

$$L_{WP}(f) = a_P(f) + b_P(f) \lg \left[\frac{v - v_{ref}}{v_{ref}} \right] \quad (1.2)$$

where $v_{ref} = 70$ km/h. The coefficients $a(f)$ and $b(f)$ for each main vehicle category is given in tables. If we want to adjust the model these coefficients have to be determined. The coefficients may differ from country to country as there may be systematic differences in vehicle fleet and road surfaces. This is further investigated in the IMAGINE project, see www.imagine-proj.org.

The Nordic road authorities has decided to implement a hybrid model of Nord 2000 and Harmonoise in 2006. In principle the propagation model of Nord 2000 shall be used together with the source model of Harmonoise. However, during the process, the source coefficients of Harmonoise will, if necessary, be revised to fit Nordic source data better. This project will provide an input to this revised model. On assignment by the Nordic road authorities the Nordic institutes SP, Delta, SINTEF and VTT have been given the task to prepare such an implementation.

1.2 Status of the IMAGINE project

The IMAGINE project has one work package, WP 5, which has the task to adapt the Harmonoise source model to different regions of Europe. One task is also to review the model for heavy vehicles and the values of the different coefficients. Within WP 5 the results of this Swedish investigation will be considered. As the IMAGINE projects does not end until December 2006 proposals given in this report have to be considered as provisional. Further adaptations to other European data may cause changes.

1.3 Aim

The aim of this project has been to review the Harmonoise source model for heavy vehicles.

1.4 Organization of the project

The project has included the following tasks

- Laboratory measurements of propulsion noise under laboratory conditions by Volvo
- Joint measurements by Volvo and SP at Hällered proving ground
- Other measurements by SP
- Analysis of earlier measurements

Due to coming discussions within the IMAGINE project the Volvo laboratory measurements which have been reported separately, [4-8], will not be dealt with in detail. Future conclusions will have to be based on all European knowledge, including this report and the Volvo reports.

2 Separation of tyre/road and propulsion noise

2.1 General

According to the Harmonoise model propulsion noise and tyre/road noise are separated. This is both a strength and a weakness. Principally, it is, of course, a huge advantage to make this separation but the weakness is that it makes the modelling quite difficult and it is easy to get erroneous results due to limited access to accurate data. Within this project it has not been possible to make a full validation of the basic model. However, some efforts were made and they are reported in the following.

2.2 Methods to estimate rolling and propulsion noise

In Harmonoise each vehicle is modelled as two moving point sources at different heights. A certain proportion p_R % of the rolling (tyre/road) noise is associated with the lowest source and $(1-p_R)$ % with the highest one. For propulsion noise p_P % associated with the highest source and $(1-p_P)$ % with the lowest one. According to the Harmonoise model the sources for heavy vehicles are located at the heights 0,01 m and 0,75 m respectively and 20% of the sound power of each source is allocated to the other source.

Assuming we have a sound power W_1 at source height 0,01 m and a sound power W_2 at 0,3 m and 0,75 respectively we get

$$W_1 = p_R W_R + (1 - p_P) W_P \quad (2.1)$$

$$W_2 = p_P W_P + (1 - p_R) W_R \quad (2.2)$$

where

W_R and W_P (The levels are denoted L_{WR} and L_{WP} respectively) is the sound power level of the rolling and propulsion noise respectively. The sound exposures are

$$E_1 = C_1 W_1 \quad (2.3)$$

$$E_2 = C_2 W_2 \quad (2.4)$$

or in levels

$$L_{E1} = 10 \lg \left(\frac{E_1}{E_0} \right) = 10 \lg \left(\frac{C_1 W_0}{E_0} \right) + 10 \lg \left(\frac{W_1}{W_0} \right) = -L_{C1} + L_{W1} \quad (2.5)$$

$$L_{E2} = L_{W2} - L_{C2} \quad (2.6)$$

$E_0 = 4 \cdot 10^{-10} \text{ Pa}^2\text{s}$ and $W_0 = 10^{-12} \text{ W}$. C_1 and C_2 are transfer functions between sound power and sound exposure for the test situation. The transfer functions are functions of the speed of the vehicle. We measure the total sound exposure level

$$L_E = L_{E1} + L_{E2} = 10 \lg \left(10^{0,1(L_{W1} - L_{C1})} + 10^{0,1(L_{W2} - L_{C1})} \right) \quad (2.7)$$

In the Harmonoise source model $p_R = p_P = 0,8$. The sound power levels, L_{WR} and L_{WP} , with possible corrections are given by eq. (1.1) and (1.2). Some examples of transfer functions L_{C1} and L_{C2} for different receiver and source heights are given in figure 2.1. These transfer functions have been calculated using the Nord 2000 soundpropagation model, which, in this case, will yield the same result as the Harmonoise propagation model. The speed dependence is given by

$$L_{C1} = L_{C1}(50) + 10 \lg \left(\frac{v}{50} \right) \quad (2.8)$$

$$L_{C2} = L_{C2}(50) + 10 \lg \left(\frac{v}{50} \right) \quad (2.9)$$

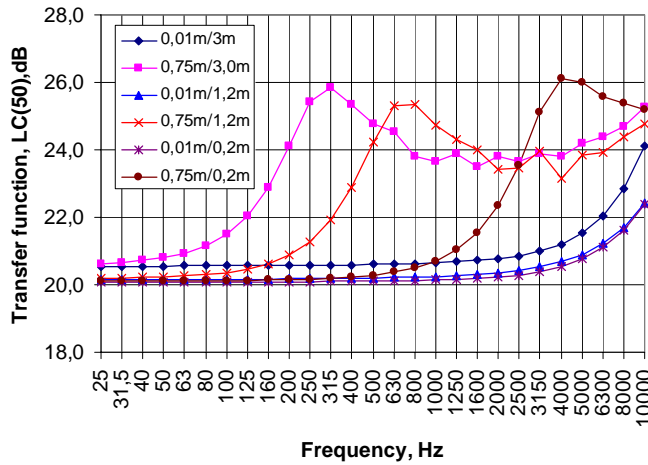


Figure 2.1 Calculated transfer functions for some different source heights and receiver positions 7,5 m from the centre line of the vehicle

As there are too many unknown variables it is not possible to determine everything from simple pass-by measurements. Different assumptions have to be made. Some examples:

1. Determination of L_{WR} from coast-by (engine switched off or idling) measurements.

In this case $W_P = 0$ and we thus get

$$W_1 = p_R W_R \quad (2.10)$$

$$W_2 = (1 - p_R) W_R \quad (2.11)$$

which, together with (2.7) yields

$$L_{WR} = L_E - 10 \lg \left(10^{-0,1L_{C1}} \cdot p_R + 10^{-0,1L_{C2}} \cdot (1 - p_R) \right) \quad (2.12)$$

Using the Harmonoise given value $p_R = 0,8$ and the precalculated transfer functions in figure 2.1 we can now determine L_{WR} . Details on measurement procedures can be found in [9].

Note If the road surface is different from normal hard asphalt the transfer functions given in figure 2.1 will no longer be valid. In such cases, e.g. for porous asphalt new transfer functions have to be calculated taking the changed acoustic impedance of the road surface into account.

By measuring at different speeds it is simple to apply regression analysis to obtain the coefficients in equation (1.1). For passenger cars the tyre/road noise may dominate so much that the engine can be kept running during the measurements.

2. Determination of L_{WR} from normal traffic

Depending on frequency, speed, vehicle type and road surface one or the other of rolling and propulsion noise will dominate. By zeroing the least important source a reasonable estimate of the other one could be obtained.

3. Transfer matrix method

Assuming that the sound source is modelled by two point sources $i = 1, 2$ and that we measure the sound exposure E_j at $j = 1, 2, \dots, N$ microphone positions and that each source – microphone transfer function is described by C_{ij} we get the following equations:

$$C_{11}W_1 + C_{21}W_2 = E_1 \quad (2.13)$$

$$C_{12}W_1 + C_{22}W_2 = E_2 \quad (2.14)$$

$$C_{1N}W_1 + C_{2N}W_2 = E_N \quad (2.15)$$

or written in matrix form

$$CW = E \quad (2.16)$$

or

$$W = C \setminus E \quad (2.17)$$

This method is described in [3].

It is recommended to average over a great number of vehicle pass-bys. The method has several limitations and the results have to be handled with care. At low frequencies the resolution is not sufficient to distinguish between different source heights. The transfer functions are not 100% correct as they assume a certain distribution in height which may be different from that of the actual test case.

2.3 Some examples

The transfer matrix method has been applied on a few measurements on heavy vehicles. In figure 2.2-2.3 some measurements are shown using 3 different microphone positions at the heights 0,2 m, 1,2 m and 3,0 m. The left figure shows results of the transfer matrix method of a pass-by measurement using measured sound exposure levels at the different microphone positions and calculated transfer functions for the Harmonoise source

heights. The right figure shows the calculated ratio between the low and high source using the revised Harmonoise model SE Nord 2005 discussed later. We can see that the tyre/road peak at 630-800 Hz is rather well detected whereas the spread is quite big at high frequencies. For these we would probably need to average over many measurements. Although the agreement is by no means perfect the results still indicate that the Harmonoise model is reasonable.

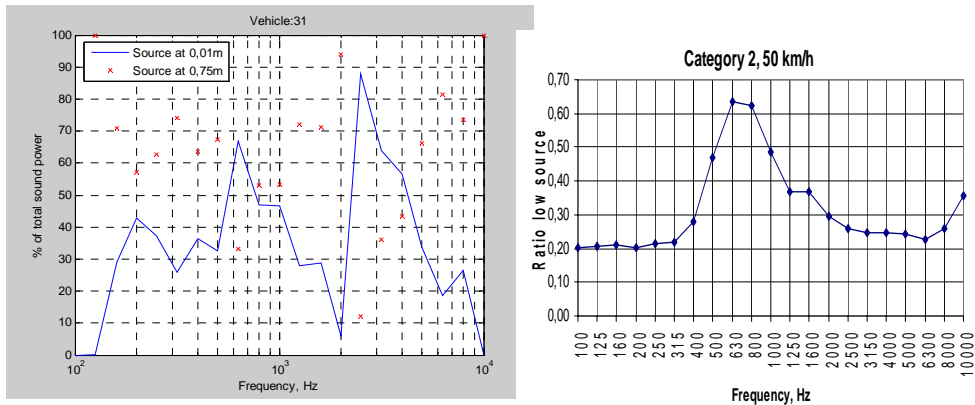


Figure 2.2 Volvo category 2 vehicle

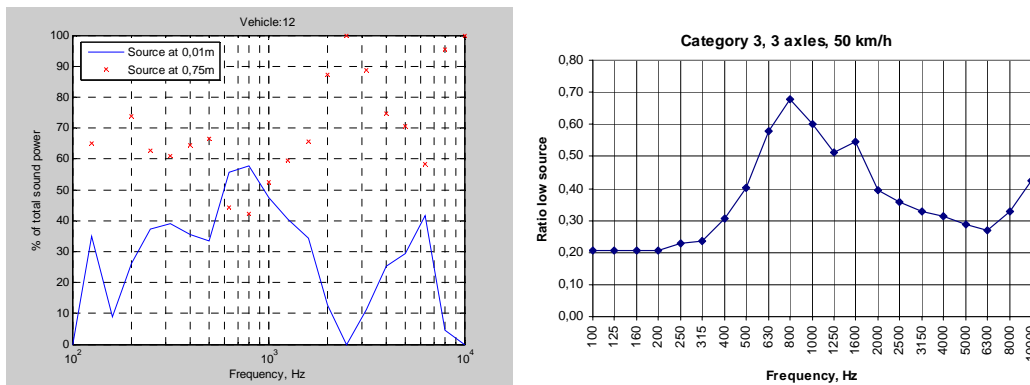


Figure 2.3 Measured (left figure, approximate solution) and calculated (revised Harmonoise model) ratio of tyre/road sound power and the total sound power. Volvo category 3 vehicle at 50 km/h.

3 Reanalysis of data on heavy vehicles in Nord 2000

In Nord 2000 there are data bases including heavy vehicles. The largest data base is the Danish one. This data base has been used to modify the coefficients in the Harmonoise equations and the new coefficients are shown in table 3.1. Category 2 vehicles are heavy vehicles with 2 axles whereas category 3 vehicles are heavy vehicles with 3 axles and more. The coefficients a_R for category 3 vehicles refer to $N=4$ axles. For another number of axles correct as

$$a_R(N) = a_R(N = 4) + 10 \lg\left(\frac{N}{4}\right) \quad (3.1)$$

When making these coefficients some assumptions have been made in order to be able to handle the distribution between rolling noise and propulsion noise:

- The speed coefficients $b_R(f)$ have assumed to be equal to those of category 1 vehicles (passenger cars), the coefficients of which have been determined assuming that tyre/road noise dominates at high speeds.
- The coefficients $a_R(f)$ have been fitted to different data using the original Harmonoise coefficients as starting point. The coast-by measurements at Hällered, see clause 4, have also been used for calibration.
- Propulsion noise has been what is left when rolling noise has been determined.

Table 3.1 Revised Harmonoise coefficients for heavy vehicles based on Danish Nord 2000 data.

	Category 2		Category 3		Category 2		Category 3	
	a_R	b_R	a_R	b_R	a_P	b_P	a_P	b_P
25	76,5	33,0	79,5	33,0	97,0	0,0	97,7	0,0
31,5	76,5	33,0	79,5	33,0	97,7	0,0	97,3	0,0
40	76,5	33,0	79,5	33,0	98,5	0,0	98,2	0,0
50	78,5	30,0	81,5	30,0	98,5	0,0	103,3	0,0
63	79,5	30,0	82,5	30,0	101,5	0,0	107,9	0,0
80	79,5	30,0	82,5	30,0	101,4	0,0	105,4	0,0
100	82,5	41,0	85,5	41,0	97,0	0,0	101,0	0,0
125	84,3	41,2	87,3	41,2	96,5	0,0	101,0	0,0
160	84,3	42,3	87,3	42,3	95,2	0,0	101,3	0,0
200	84,3	41,8	87,3	41,8	99,6	0,0	101,3	0,0
250	87,4	38,6	90,4	38,6	100,7	8,5	102,5	8,5
315	88,2	35,5	91,2	35,5	101,0	8,5	103,0	8,5
400	92,0	31,7	95,0	31,7	98,3	8,5	102,0	8,5
500	94,1	25,9	97,1	25,9	94,2	8,5	101,4	8,5
630	96,5	26,5	99,5	26,5	92,4	8,5	99,4	8,5
800	96,8	32,5	99,8	32,5	93,4	12,5	95,1	8,5
1000	95,6	37,7	98,6	37,7	95,5	12,5	95,8	8,5
1250	93,0	41,4	96,0	41,4	96,0	12,5	95,3	8,5
1600	93,9	41,6	96,9	41,6	93,8	12,5	92,2	8,5
2000	91,5	42,3	94,5	42,3	93,4	12,5	93,2	8,5
2500	88,1	38,9	91,1	38,9	92,1	12,5	90,7	8,5
3150	86,1	39,5	89,1	39,5	90,1	12,5	88,8	8,5
4000	84,2	39,6	87,2	39,6	87,9	12,5	87,5	8,5
5000	80,3	39,8	83,3	39,8	85,6	12,5	85,9	8,5
6300	77,3	40,2	80,3	40,2	85,7	8,5	86,9	8,5
8000	77,3	40,8	80,3	40,8	82,6	8,5	83,8	8,5
10000	77,3	41,0	78,3	41,0	79,5	8,5	80,3	8,5

The difference to the original Harmonoise coefficients is given in table 3.2.

Table 3.2 The difference between table 3.1 and the original Harmonoise coefficients

Category 2		Category 3(4 axles)		Category 2		Category 3	
a_R	b_R	$a_R^{1)}$	b_R	a_P	b_P	a_P	b_P
0,0	0,0	0,0	0,0	0	0	0	0
0,0	0,0	0,0	0,0	0	0	0	0
0,0	0,0	0,0	0,0	0	0	0	0
0,0	0,0	0,0	0,0	0	0	0	0
0,0	0,0	0,0	0,0	0	0	-1,6	0
0,0	0,0	0,0	0,0	0	0	0,1	0
0,0	0,0	0,0	0,0	0	0	0,2	0
0,0	0,0	0,0	0,0	0	0	-0,2	0
-0,4	0,0	-0,4	0,0	0	0	1,4	0
0,0	0,0	0,0	0,0	0	0	-1	0
0,0	0,0	0,0	0,0	0	0	-1	0
0,0	0,0	0,0	0,0	0	0	-1	0
0,0	0,0	0,0	0,0	0	0	0,4	0
0,0	4,4	0,0	4,4	0	0	2,2	0
2,7	5,3	2,7	5,3	0	0	0	0
2,4	9,0	2,4	9,0	1,3	4	0	0
3,4	8,6	3,4	8,6	1,7	4	0	0
3,4	7,9	3,4	7,9	1,7	4	0	0
5,0	7,5	5,0	7,5	-1,4	4	-1,6	0
5,0	7,2	5,0	7,2	-1,5	4	-0,7	0
5,0	2,5	5,0	2,5	-1,2	4	-2	0
5,0	2,1	5,0	2,1	-1,1	4	-2,8	0
5,0	0,7	5,0	0,7	-1,4	4	-3,4	0
3,0	0,1	3,0	0,1	-1,7	4	-2	0
0,0	0,5	0,0	0,5	0,4	0	-1	0
0,0	1,1	0,0	1,1	-1,7	0	2	0
0,0	1,3	-2,0	1,3	-3,8	0	0,1	0

The results of these fitting procedures are shown in figure 3.1 – 3.5. The results of this fitting of Danish data will in the following be called DK Nord 2005 whereas the corresponding fitting to Swedish data, which includes a road surface correction of a_R to the Danish data will be called SE Nord 2005.

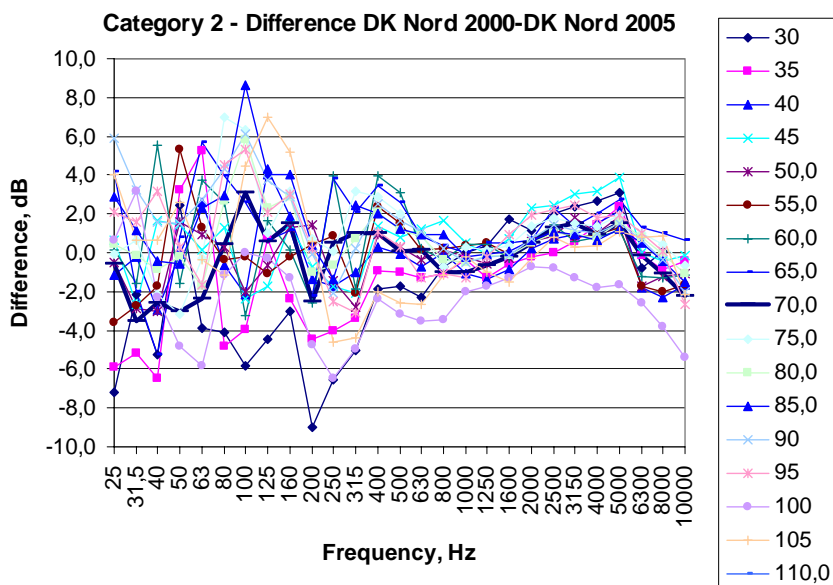


Figure 3.1 Difference between Danish Nord 2000 data and the revised Harmonoise model. Category 2 vehicles. Mean difference in L_{EA} 0,1 dB, $s = 0,9$ dB. 30, 65, and > 90 km/h have rather few samples (< 22)

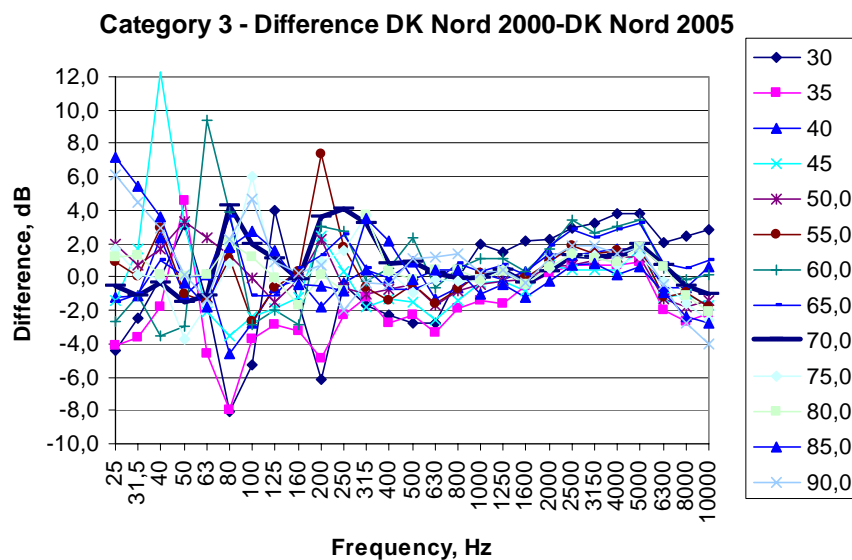


Figure 3.2 Difference between Danish Nord 2000 data and the revised Harmonoise model. Category 3 vehicles. Mean difference in $L_{EA} = 0,1$ dB, $s = 0,7$ dB. 30, 35, 60 and 65 km/h have rather few samples (< 25)

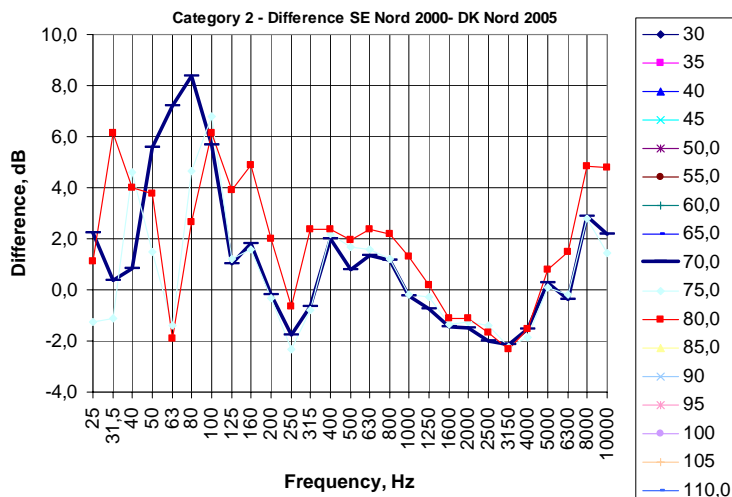


Figure 3.3 Difference between Swedish Nord 2000 data and the revised Danish Harmonoise model. Category 2 vehicles. Mean difference in $L_{EA} = 0,3 \text{ dB}$, $s = 0,5 \text{ dB}$. Other speeds had too few samples

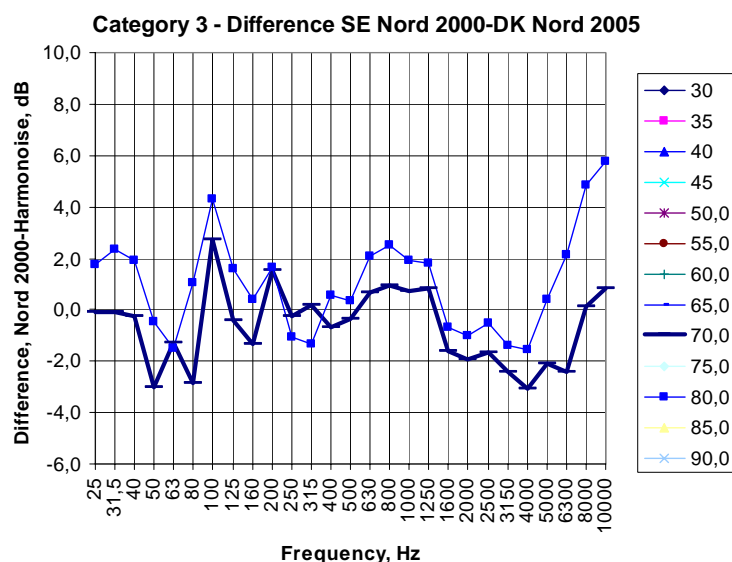


Figure 3.4 Difference between Swedish Nord 2000 data and the revised Danish Harmonoise model. Category 3 vehicles. Mean difference in $L_{EA} = 0,3 \text{ dB}$, $s = 0,5 \text{ dB}$. Other speeds had too few samples

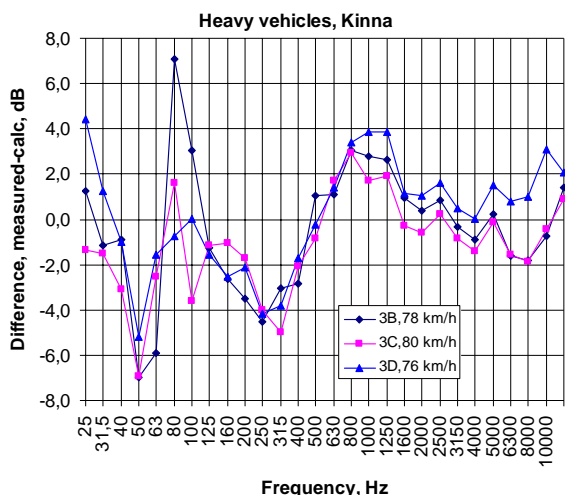


Figure 3.5 Difference between some new Swedish measurements and the revised Danish Harmonoise (DK Nord 2005). The measured LEA is 0,9-2,1 dB greater.

There seems to be a systematic difference between Danish and Swedish data. In Sweden the measured values tend to be higher around 800 Hz and lower around 3150 Hz. The reason for this is not known. The same difference tends to be present to an even greater extent for category 1 vehicles. 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 accordingly.

In order to correct for the difference the corrections given in table 3.2 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.

Table 3.1 Corrections applied to the tyre/road coefficient a_R .

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 new results with this revised model, called SE-Nord 2005 are shown in figure 3.6 and 3.7 for the old Swedish Nord 2000 data.

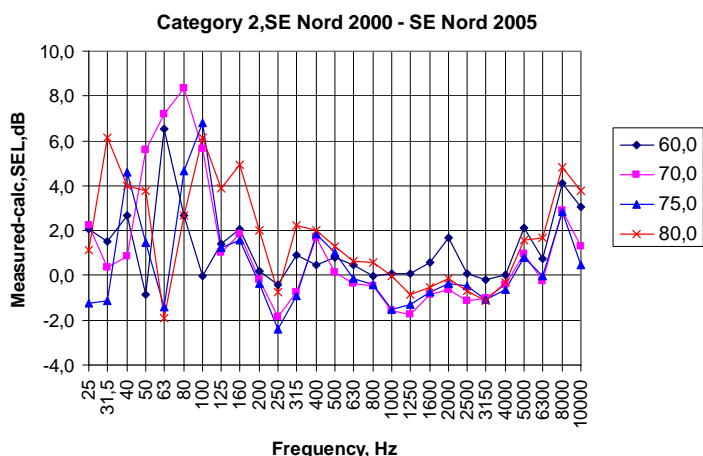


Figure 3.6 Difference between Swedish Nord 2000 measurements and the revised DK Nord 2005 (SE Nord 2005). The measured values are -0,6 dB - +0,4 dB greater.

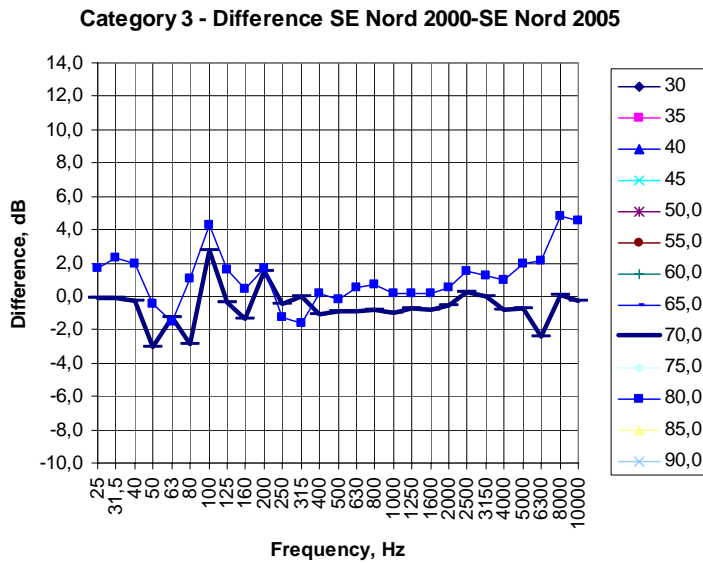


Figure 3.7 Difference between Swedish Nord 2000 measurements and the revised DK Nord 2005 (SE Nord 2005). The measured values are $-0,8 \text{ dB} - +0,4 \text{ dB}$ greater.

4 Measurements at Volvo proving ground in Hällered

4.1 Description of the measurement procedure

In order to be able to perform a series of well controlled measurements a test series was carried out at Volvo proving ground at Hällered outside Borås. 4 different Volvo trucks were tested: 2 axles, 3axles, 5 axles and 8 axles. They were driven by the same driver. The aim was to investigate the effect of normal driving patterns in urban situations.

The first test was an acceleration test with 5 microphones, M1-M5, one after the other, 15 m apart. The vehicle and the measurements started 20 m before the first microphone when the vehicle started moving and ended 20 m after the last microphone. At each microphone the SEL-value was evaluated for $\pm 20 \text{ m}$ and the speed was measured at the middle microphone (M3). Measurements were also taken with the vehicle cruising and coasting (engine switched off). In these cases only M3 was evaluated. The set-up was the standard one, 7,5 from the centre line of the vehicle and at a height of 1,2 m. Some additional microphone heights were included at position M3 to use for special evaluations.

The vehicles tested were

1. Volvo FL 220, RXK 439, 2 axle truck, 15 tons
2. Volvo FH 16, MWF 582, 3 axle truck, 18 tons
3. Volvo FH 12, SYP 661 33, 5 axle truck, 47 tons
4. Volvo FH 16, MWF 582, trailer (3+5 axles), 25m, 27,5 tons

Another test was to simulate corners and roundabouts with measurement points 10 m before and 10 m after the point where the road changed width. Distance and microphone height was as before.

4.2 Summary of the results (A-weighted)

The most important results are summarized in Figure 4.1. We can see that the sound exposure level is fairly constant when accelerating along the 5 microphone positions although it falls off for the two lightest vehicles after position 3. The levels are about 3 dB higher than the cruising values. As

$$L_E = L_W - 10 \lg\left(\frac{v}{50}\right) + const \quad (4.1)$$

a constant sound exposure level L_E means that the sound power level L_W approximately increases as $10 \lg(\text{speed})$ during acceleration at low speeds.

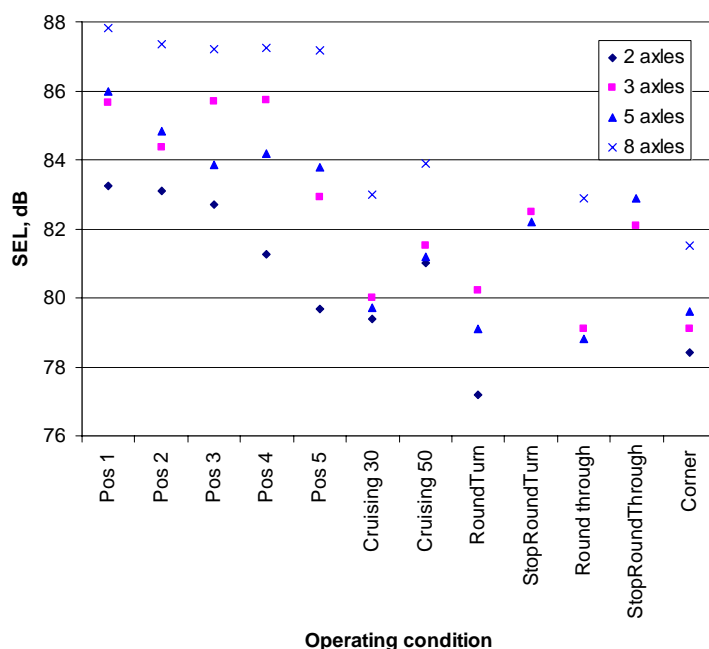


Figure 4.1 A-weighted SEL-levels during pass-by of the different microphones.

In Harmonoise acceleration is corrected for as

$$\Delta L_{acc} = C \cdot a; -2 \text{ m/s}^2 \leq a \leq 2 \text{ m/s}^2 \quad (4.1)$$

where a = the acceleration/deceleration in m/s^2 and the coefficient $C = 5,6$ for heavy vehicles. Counting backwards a 3 dB increase of propulsion noise corresponds to an acceleration of about $0,5 \text{ m/s}^2$. The 5-axle vehicle is estimated to have an average acceleration of $0,65 \text{ m/s}^2$ whereas the 8-axle vehicle, which was less loaded, had $1,2 \text{ m/s}^2$. Thus it seems that Harmonoise gives a reasonable estimate of the effects of acceleration.

For driving around corners and in a roundabout it seems clear that the noise level is significantly lower in the near neighbourhood than would be the case for free acceleration, see clause 7 for further comments.

4.3 Cruising

The Volvo measurements for cruising vehicles at constant speed have been compared with the SE Nord 2005 revised Harmonoise model. As can be seen from figure 4.2 the calculated levels are with one exception higher than the measured values. The reason for this is not clear. The trend for measurements in real traffic as reported in clause 3 rather indicates higher values. Possible explanations are that the tested vehicles were rather new and in good condition, that the test driver followed the rule book and always had a low, economic rpm or that the vehicles were equipped with more quiet tyres than normal. In any case it seems difficult to adjust the predicted levels downwards as long as it is not supported by measurements in real traffic.

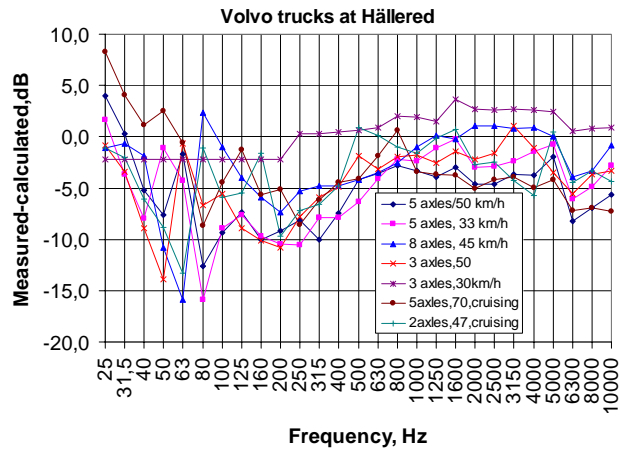


Figure 4.2 Difference between measured and predicted (using SE Nord 2005) values.

An interesting thing is that the noise level seems to be identical for the 2-axle and the 3-axle truck while cruising, see figure 4.3. This could be an indication to use the same propulsion noise for category 3B (3-axle truck) and category 2B (2-axle truck) vehicles.

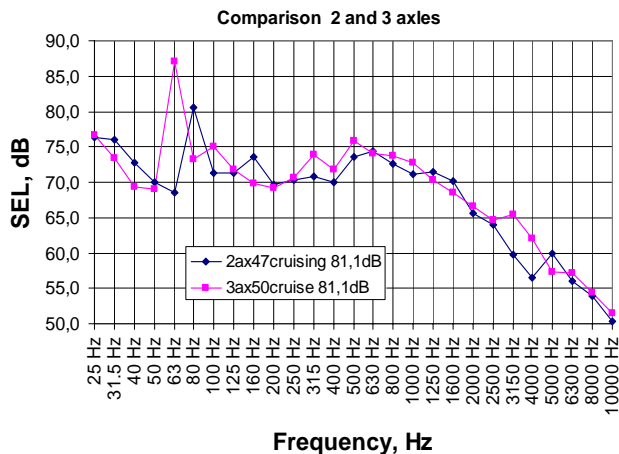


Figure 4.3 Comparison between a 2 axle and 3 axle truck.

4.4 Acceleration

Figure 4.4 shows that there is a significant effect of acceleration on a 2-axle truck and that tyre/road noise obviously is strongest around 630 and 1250 Hz. Figure 4.5 shows that the spectrum shape is almost constant when accelerating between 0-50 km/h. That is also the case for the 5-axle truck in figure 4.6.

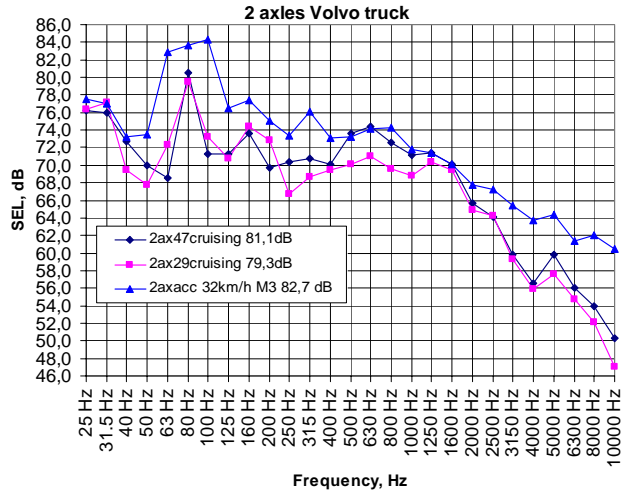


Figure 4.4 Effect of acceleration on a 2-axle truck.

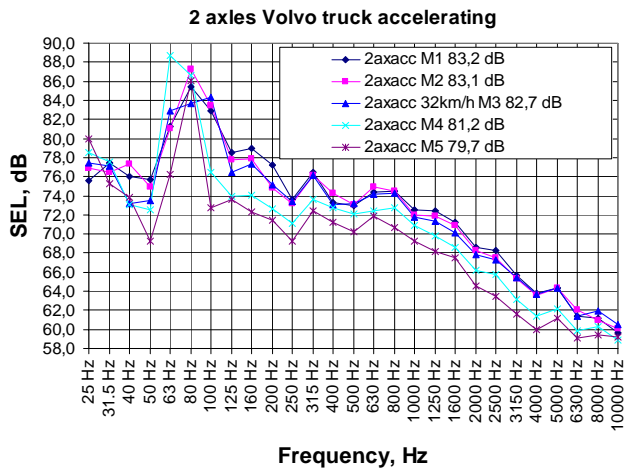


Figure 4.5 Effect of acceleration on a 2-axle truck..

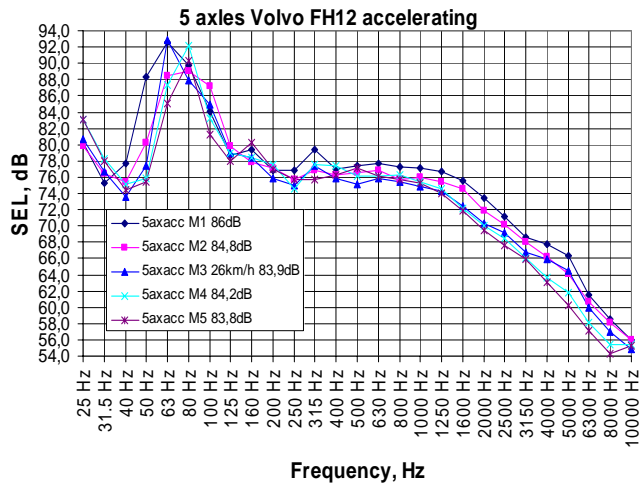


Figure 4.6 Effect of acceleration on a 5-axle truck.

Figure 4.7 shows that acceleration at low speed is louder than cruising at 50 km/h. At 70 km/h it is only around 630 Hz where tyre/road noise gets louder than for low speed acceleration.

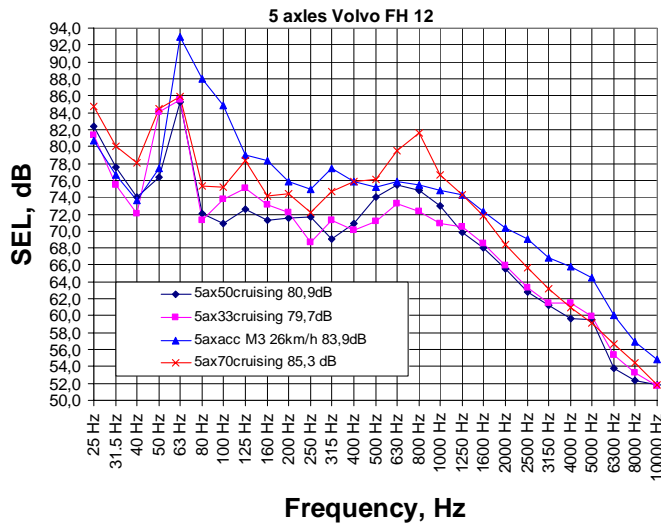


Figure 4.7 Effect of acceleration on a 5-axle truck.

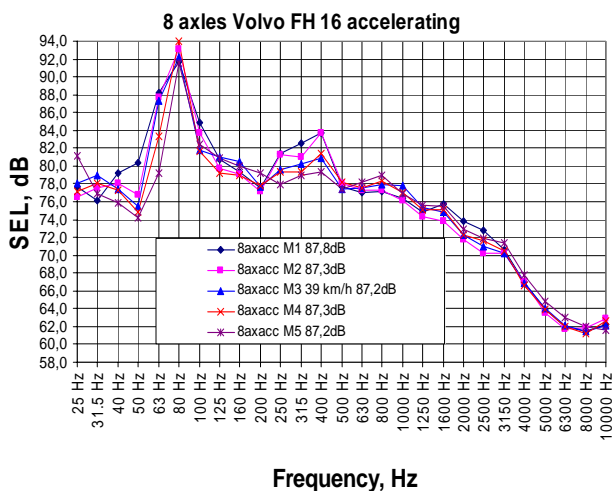


Figure 4.8 Effect of acceleration on an 8-axle truck.

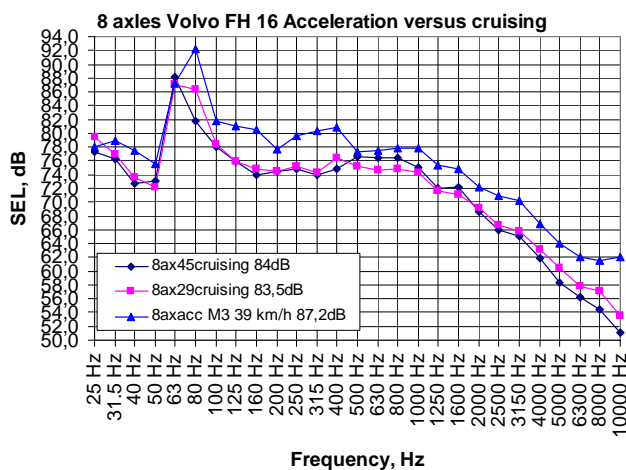


Figure 4.9 Effect of acceleration on an 8-axle truck.

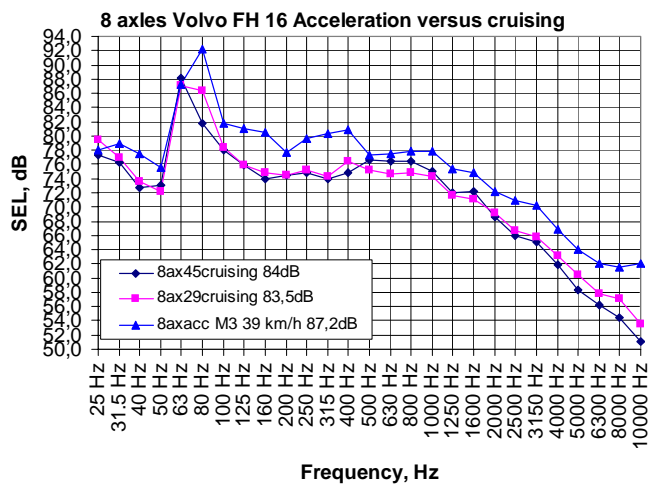


Figure 4.10 Effect of acceleration on an 8-axle truck.

4.5 Right and left side of the vehicle

Figure 4.11 shows some comparisons between measurements on the left and the right side of the vehicle. As there was only microphone on one side the operating conditions may differ a little between the measurements. The measurements are not enough to allow for any firm conclusions but the difference, if any, does not seem to be very important.

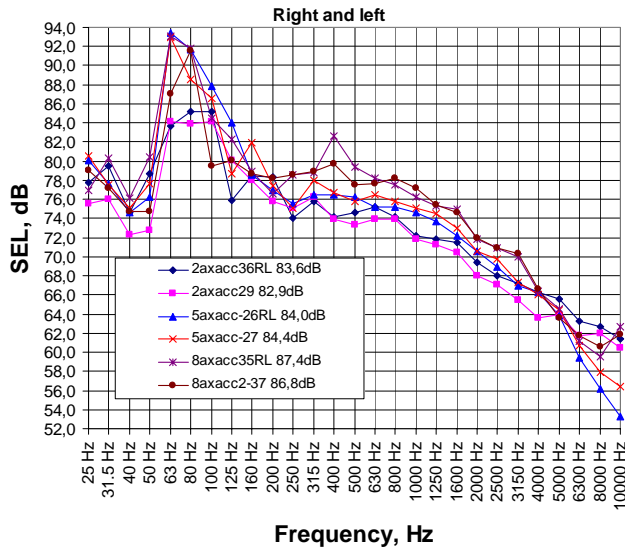


Figure 4.11 Effect of acceleration on an 8-axle truck.

4.6 Coasting

In Figure 4.12 a comparison is made between measured coasting levels 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.

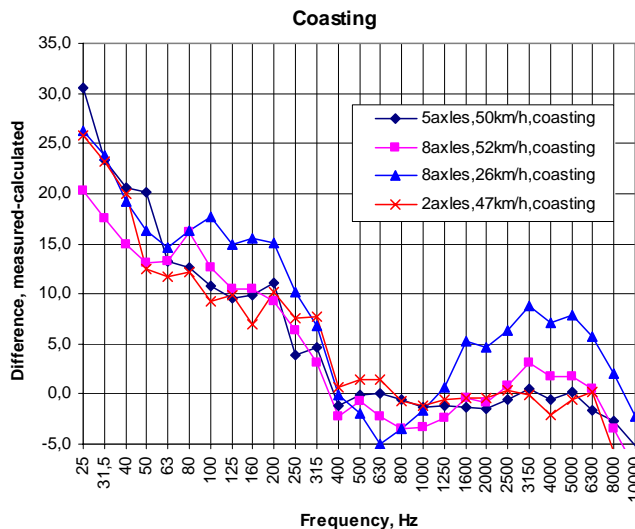


Figure 4.12 Comparison between measured coasting levels and calculated levels using the revised Harmonoise SE Nord 2005 model.

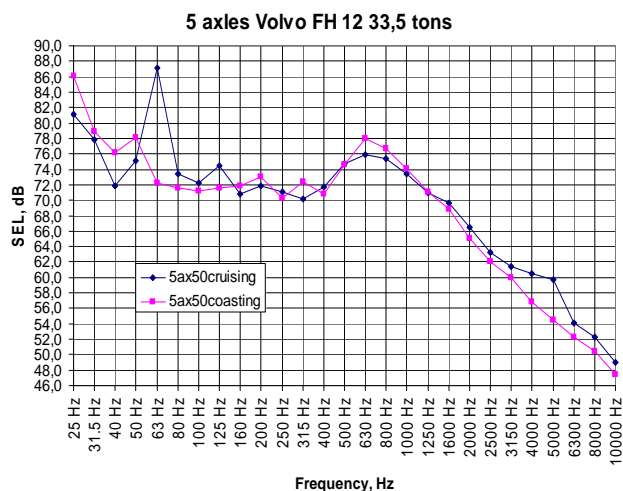


Figure 4.13 Comparison between cruising and coasting for a 5-axle truck

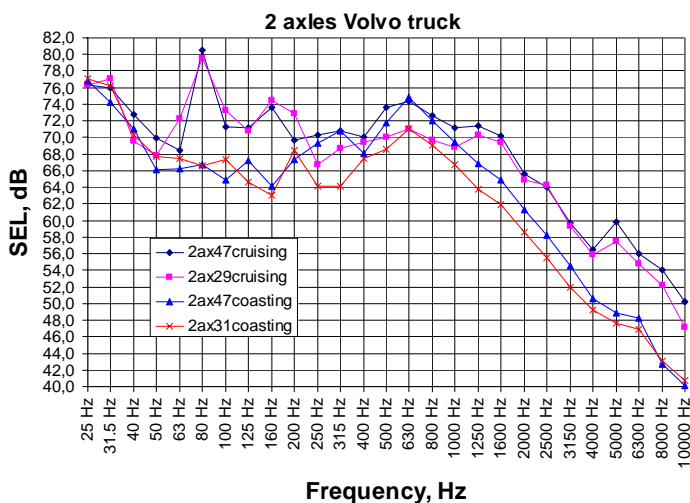


Figure 4.14 Comparison between cruising and coasting for a 2-axle truck.

5 Some other Swedish measurements

Some recent Swedish measurements shown in Figure 4.15 and 4.16 indicate that measured levels are slightly higher than calculated using the SE 2005 model. This is in contrast to the Hällered measurements which rather indicated lower values.

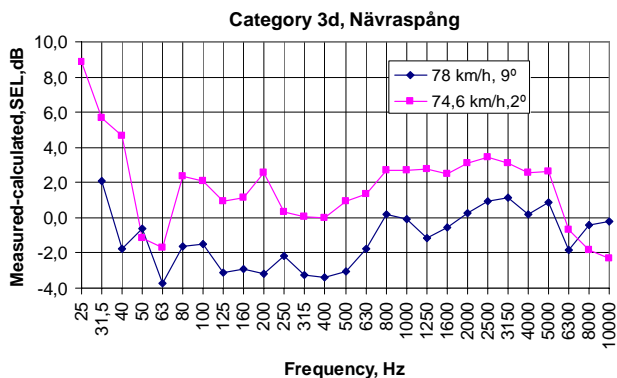


Figure 4.15 Comparison between measured coasting levels and calculated levels using the revised Harmonoise SE Nord 2005 model. 3D= 6,5 axles (average).

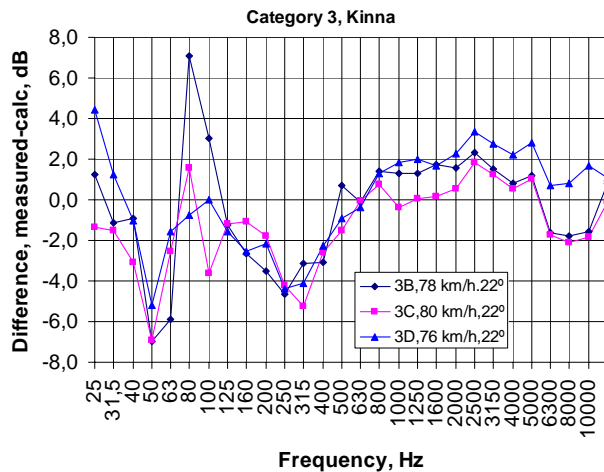


Figure 4.16 Difference between some new Swedish measurements and the revised DK Nord 2005 (SE Nord 2005). The measured values are -0,1 dB – +1,1 dB greater. 3B = truck with 3 axles, 3C truck= with 5 axles, 3D=truck with 6,5 axles.

6 Maximum levels

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 2.5 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.

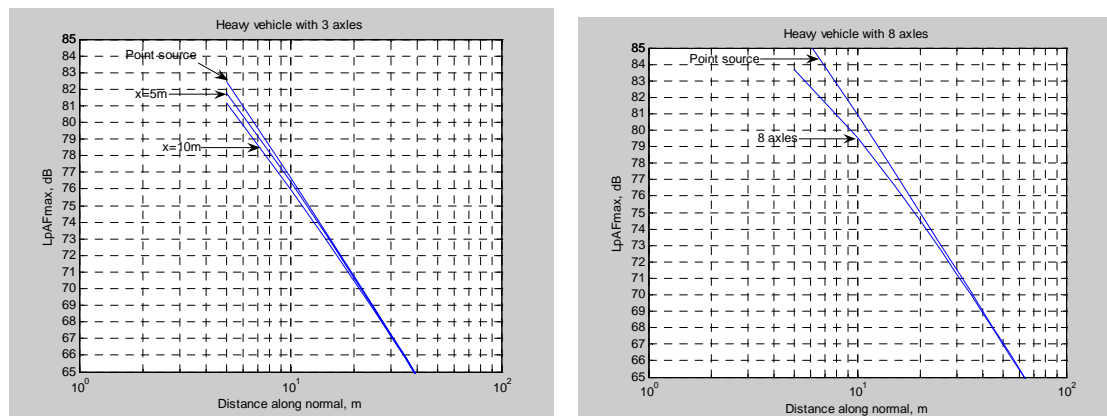


Figure 6.1 Difference between sound propagation from a point source and an extended source consisting of one point source at each axle.

7 Crossings and roundabouts

For heavy vehicles in crossings and roundabouts the situation is complicated as a slow down will be followed by acceleration which will increase the sound power level. In [10] it was shown that cars emitted less noise in crossings/roundabouts than when cruising at 50 km/h and that the SEL-level was close to that of cruising at 30 km/h. The question is

whether or not this is also true for heavy vehicles. In Figure 7.1, which is identical to figure 4.1, we can see some results. The corner and roundabout microphones were located 10 m from the corner of the virtual sidewalk.

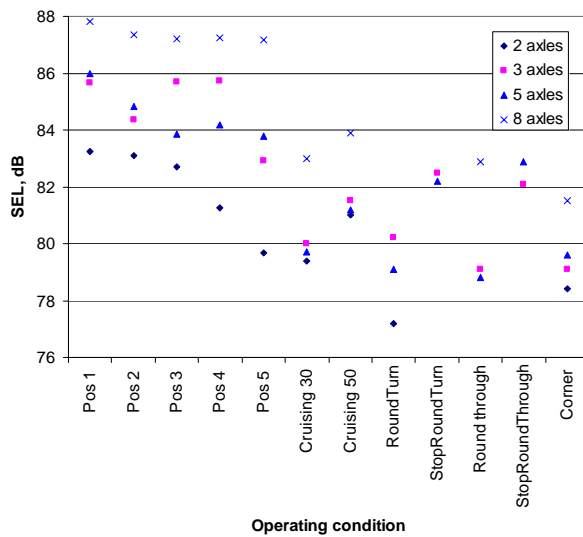


Figure 7.1 Sound exposure levels during simulated driving at corners and roundabouts.

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Figure 7.1 clearly indicates that acceleration from complete stand still increases the sound power level and that this increase is not very sensitive to the speed. In the vicinity of a roundabout or corner the sound power 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 ($0,5 \text{ m/s}^2$) according to the Harmonoise acceleration model 100 m before and after each roundabout/crossing.

8 Hill driving

8.1 General

The effect of hill driving on the noise generation has been investigated by Volvo by laboratory measurements, which are described in the following.

In uphill conditions, the driver tends to increase the power output of the engine by increasing the throttle position in order to keep a constant speed. If the grade of the hill is too steep to keep the speed constant, the gear is shifted down. This will increase the rotational speed of the engine and increase the engine torque. This driving mode will generally increase the propulsion noise. In addition to this effect the fan can lead to

increased noise in uphill conditions. When the engine load increases and the speed of the vehicle decreases, the cooling of the engine needs to be enhanced, since the natural cooling from the wind decreases. In some cases the noise from the fan is the dominating noise source and the fan noise can hence not be overseen in situations where the engine temperature is raised during a long period of time such as driving in long uphill slopes.

Downhill driving increases the vehicle speed but in order not to exceed allowed speed the vehicle has to be decelerated with engine brakes or retarders; only using the wheel brakes would result in immediate worn out brakes due to the high temperatures. There are different types of engine brakes, where the exhaust brake (EPG, exhaust pressure governor) and compression release brake are the most common ones. Generally, engine brakes generates about as much noise during the brake performance as a vehicle in full load acceleration. However, variations of the engine brakes are large. Engine brakes are also present when driving on horizontal road. When driving with the cruise controller the engine brakes are engaged each time the throttle pedal is released. Engine brake noise is greatly related to the engine speed and brake torque. To obtain as great brake torque as possible, the engine has to shift down the gear, resulting in a full load situation for the vehicle. That is the case in a long moderate downhill slope or a short steep slope when the vehicle mass is pushing on the wheels.

8.2 Laboratory measurements

Three different sets of measurements were performed in the noise and vibration laboratory at Volvo to study the propulsion noise. They are thoroughly presented in the measurement reports [5, 6 and 7].

8.2.1 The test objects

In all cases a long haul or long distance like truck was simulated with the same type of engine: 480 hp 6-cylinder in-line, but different gearboxes: an automatically controlled manual gearbox (Ishift) in the first case and a manual gearbox in the second and third measurement. In the first set of measurements the truck was built up around the engine and gearbox in the powertrain rig at the laboratory, see picture 1 (explained on page 3 in [5]).

The measurements in [6] and [7] were performed in the truck noise chamber on a complete vehicle, see picture 2 (explained on page 3 in [6]). More photos of the vehicle are included in appendix 1 in [6 and 7]. The simulated total vehicle load was 30 tonnes in the powertrain rig and 18 tonnes in the truck chamber.



Figure 8.1 Powertrain rig (left) and Truck noise chamber (right) at the Noise and Vibration Laboratory, Volvo Trucks Göteborg

8.2.2 Sound power measurement

The sound power measurement according to the standard ISO 3744 was chosen as test method in both rigs. The method is described on page 4 in [5] and [6]. In the first set of measurements 16 microphones were positioned around a parallelepiped reference box enclosing the test object. In [6] and [7] 14 microphone positions were used. The microphone positions are pictured in appendix 2 of all reports.

In the first two studies the propulsion noise was measured during constant speed from 5 to 85 km/h with an interval of 5 km/h with most suitable gear, i.e. the gear which results in an engine speed within the economy range. In some runs a lower gear was selected to resemble a more aggressive driving style. The influence of vehicle load and road gradient was also studied. The results are presented both as overall levels versus vehicle speed and engine speed and as sound power level for each third octave band. Regression analysis was made based on the overall levels in uphill and downhill driving.

The equivalent sound power level, in third octave bands, was additionally measured during a designed city cycle in the truck noise chamber. The city cycle is described on page 6 in appendix 3 in [7]. It included constant speed driving at different velocities as well as starting and turning of the engine, acceleration, engine braking and low idling. The overall sound power variation with time, with a time resolution of 2,3 seconds, is also presented together with the recorded engine speed, dyno roller speed (considered equal to the vehicle speed) and the tractive force of the roller (equal to the tractive force that the vehicle has to overcome). A correlation study of the sound power level and the different recorded parameters is presented in appendix 5 of [7].

8.2.3 Measurement results

The measured noise levels when simulating driving at constant speed in 50-55 km/h on positive road grades and 35-50 km/h on negative road grades are presented in figure 8.2 and 8.3 respectively. Since different vehicle loads were simulated, it is not possible to directly compare the sound power levels. The load on the engine increases proportional to the vehicle load and road grade. It can be seen that the heavier vehicle, 30 tonnes, in the powertrain rig produces greater sound levels which leads to a stronger correlation to the road grade, for both positive and negative grades, than the vehicle in the truck noise chamber.

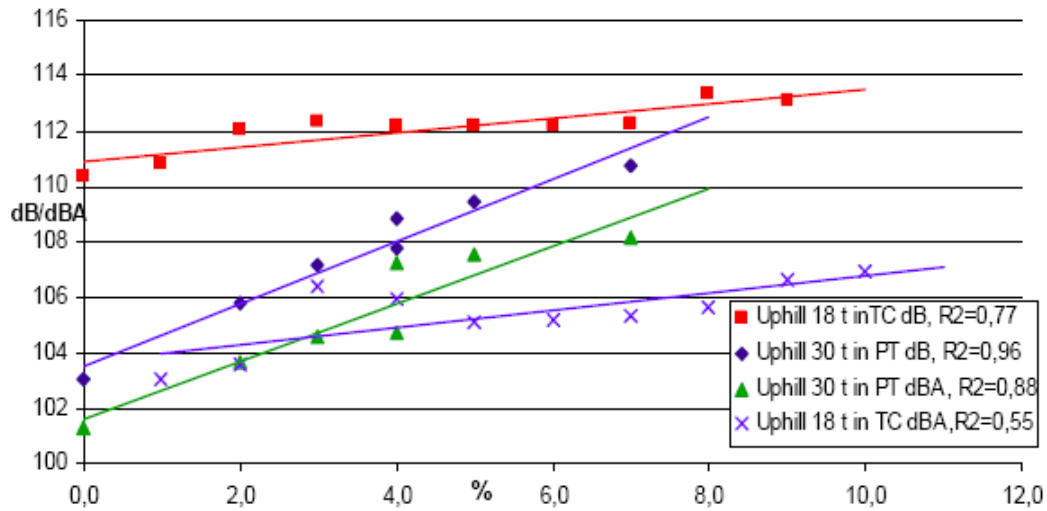


Figure 8.1 OAL for increasing road grade % in Powertrain rig (PT) and Truck noise chamber (TC)

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

$$a = g \cdot \sin(\text{angle of slope}) \approx 10 \cdot \text{slope} \% / 100 \quad (8.1)$$

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

$$\Delta L = 5,6 \cdot a = 5,6 \cdot \text{slope} \% / 10 \quad (8.2)$$

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.

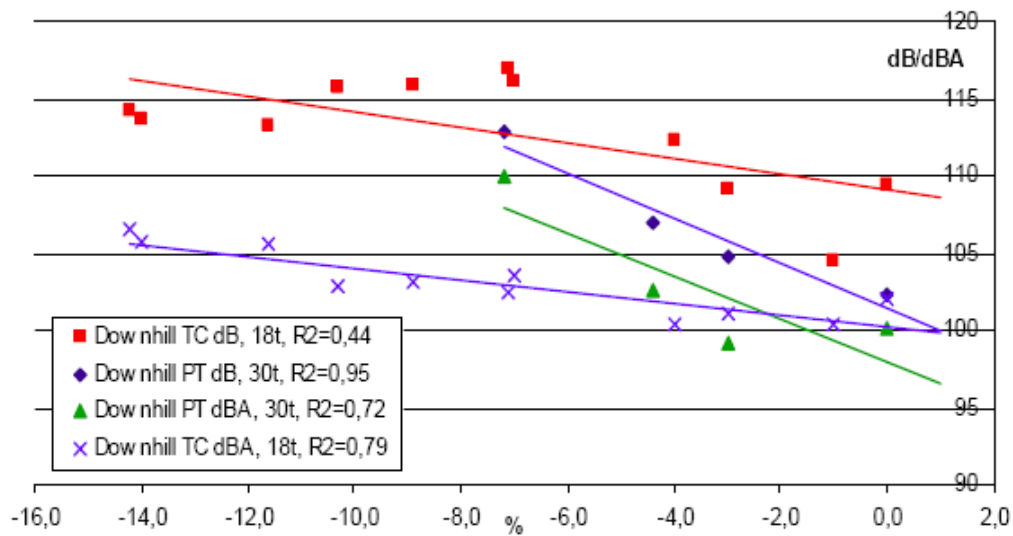


Figure 8.2 OAL for decreasing road grade % in Powertrain rig and Truck noise chamber

For negative road grades the noise increased with 0,4 dBA/% road grade in the powertrain rig and 1,4 dBA/% road grade in the truck noise chamber. It should be remarked that the vehicle in the truck noise chamber was not equipped with a second engine brake system. This would have increased the noise level. The fact that the engine fan did not interfere during the measurements makes the values appear low. More measurements are needed to study the influence of the fan which is dependent on the engine temperature and hence effected by the length of the road grade.

For downhill driving Harmonoise proposes to use the same increase as for the corresponding drive downhill in those cases where the engine brake is applied. Also this seems to be in good agreement with the results shown in figure 8.2.

It must also be commented that during the measurements the target was to remain at the same constant vehicle speed on the same gear (to avoid influence of changed engine speed) at all grades. On larger slopes however, a downshifting in gear would most likely have been performed rather than staying at the same gear. This would have decreased the vehicle speed and increased the engine speed to have greater engine torque for the traction or braking situation. For road grades less than 2 % the driving performance should not be affected, but for greater slopes a correction to the model would be needed.

9 Discussion

In general the results support the Harmonoise source model in all other aspects than the coefficients in the equations yielding the sound power level of propulsion and tyre/road noise. Nordic results indicate that the speed coefficients are wrong for tyre/road noise and also that the absolute levels have to be adjusted a little. If the tyre/road noise coefficient a_R is calibrated versus the coasting measurements at Hällered one consequence is that the propulsion noise coefficient a_P has to be adjusted down. From table 3.2 we can see that the speed coefficients b_R have in general been increased substantially whereas the propulsion noise coefficients a_P have been decreased a little.

One strange detail is the road surface correction between Danish and Swedish measurements. It is not so surprising for category 1 vehicles, which has not been discussed in this report, but it is a little surprising that it is necessary to apply such a correction for heavy vehicles. In the basic Harmonoise model no surface correction is applied on heavy vehicles, a fact, which indicates that truck tyres are not as sensitive to the road surface as car tyres. However, the differences between Danish and Swedish measurements are quite systematic and we have not been able to find any other solution than to apply this correction.

As to acceleration it is obvious that it has to taken into account for heavy vehicles. The sound exposure level increases significantly during acceleration at low speeds and it is not possible to make accurate calculations for heavy vehicles in urban traffic without correcting for it. May be one could quite simply add a default acceleration of approximately $0,5 \text{ m/s}^2$ for heavy vehicles in urban traffic.

For driving on roads with gradients the Volvo laboratory measurements support the simple Harmonoise level quite well at least if the gradient is small. What remains to be done is to make a model where the slow down in speed when driving on long slopes like those in the Alps is properly taken into account. If this is not done we cannot correctly calculate the tyre/road noise.

10 References

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