ROAD TRAFFIC:
VEHICLE NOISE EMISSION

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Title:
Noise Emission from Road Vehicles

Abstract:

A method for the determination of source parameters for estimation of road vehicle noise has been developed. The main parts of the method have been tested with measurements and this verifies that the method can be used in practice. The method, as finally formulated, has not been tested, and this should be done in a Round-Robin test. Despite this, it is recommended to forward the method suggestion to the International Organisation for Standardisation (ISO). This is due to the lack of a corresponding method and the current need for the method within the EU. The method is needed in view of the development of new noise mapping methods (HARMONOISE) with background in the recent EU noise directive.

The method estimates the expected value of the sound power of a population of vehicles. Furthermore the method estimates the weight of the sub-sources in the vehicle model and the ground impedance of the road surface. The method is based on statistical modelling and gives in particular estimates of the expanded uncertainty (ISO GUM) for all of the above mentioned parameters. The report gives, together with two previous reports [SINTEF Report STF40 A02050, SINTEF Report STF40 A03063], the background for the suggested method.
Preface

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The work on this project is closely related to ongoing work in the EU project HARMONOISE, http://www.harmonoise.org. Participation in this work has been important for the measurement method suggested.

The following people have been involved in the project:

- Jørgen Kragh, Delta Acoustics & Vibration, Denmark
- Hans Jonasson, SP Swedish National Testing and Research Institute
- Gunnar Taraldsen, Svein Storeheier, Asbjørn Ustad, and Truls Berge, SINTEF, Norway

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Most of the work was carried out in 2002 and 2003, but the final formulation of the suggested method was initiated and finalized in December 2003.

The suggested method is the main result and is included as an appendix. The reader is advised to read this appendix before reading this report.

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*Trondheim, January 2004*
Contents

Preface i

List of figures iv

1 Introduction 1
   1.1 Current noise policy strategies 1
   1.2 Vehicle noise 3
   1.3 Deterministic modeling of a road vehicle noise source 4

2 The source-to-microphone transfer function 7
   2.1 Height of microphone 7
   2.2 Distance from vehicle to microphone 8
   2.3 Road segment length 11
   2.4 Speed of vehicle 11
   2.5 Temperature 12
   2.6 Ground impedance 13
   2.7 The exposure level difference 13

3 Estimation based on a single vehicle pass-by 17
   3.1 Elementary estimation of sound power 17
   3.2 Estimation of sound power with normally distributed errors 18
      3.2.1 The accuracy of the estimator 19
   3.3 Estimation of sound power with log-normal errors 20
3.3.1 The accuracy of the estimator ........................................... 21

4 Estimation of the mean sound power of a population of vehicles 23
  4.1 The sound exposure from a road segment .............................. 23
  4.2 Expected sound power .................................................... 25
  4.3 Expected sound power given the speed ............................... 26
  4.4 Expected sound energy per distance road ............................ 28

5 Discussion and conclusions .................................................. 31
  5.1 Complexity ................................................................. 31
  5.2 Flow resistivity ............................................................. 31
  5.3 Weight ...................................................................... 32
  5.4 Source localization ......................................................... 33
  5.5 Sound power ............................................................... 34
  5.6 Conclusions ............................................................... 35

Bibliography ........................................................................... 38

A Proposal for Nordtest method
List of Figures

2.1 Source-to-microphone transfer function for selected microphone heights for a 1 cm pass-by at 6.75 m. ................................................................. 8
2.2 Source-to-microphone transfer function for selected microphone heights for a 1 cm pass-by at 9.25 m. ................................................................. 9
2.3 Source-to-microphone transfer function for selected microphone heights for a 30 cm pass-by at 6.75 m. ................................................................. 9
2.4 Source-to-microphone transfer function for selected microphone heights for a 30 cm pass-by at 9.25 m. ................................................................. 10
2.5 Source-to-microphone transfer function for selected microphone distances for a 1 cm pass-by for a microphone at height 2.05 m. ......................... 10
2.6 Source-to-microphone transfer function for selected road segment lengths for a 1 cm pass-by for a microphone at height 2.05 m. ......................... 11
2.7 Source-to-microphone transfer function for selected vehicle speeds for a 1 cm pass-by for a microphone at height 2.05 m. ......................... 12
2.8 Source-to-microphone transfer function for selected air temperatures for a 1 cm pass-by for a microphone at height 2.05 m. ......................... 13
2.9 Source-to-microphone transfer function for selected flow resistivities for a 1 cm pass-by for a microphone at height 2.05 m. ......................... 14
Chapter 1

Introduction

Noise is unwanted sound, and has been recognized as such back to ancient times. The current situation, and some aspects of road vehicle noise, will be commented on in this introduction.

1.1 Current noise policy strategies

In Norway the Council of State has decided to reduce the noise annoyance with 25% within year 2010 compared to the level in year 1999. This was based on recommendations of October 29th 1999 from the Ministry of the Environment, approved in the Council of State on the same date [30]. A quote:

8.5 Noise. The Government bases its efforts as regards noise on the following goals:

Strategic objective: Noise problems are to be prevented and reduced to take account of the requirements of human health and welfare.

National target: By 2010, noise annoyance shall be reduced by 25 per cent from the 1999 level.

8.5.3 Policy instruments and measures. The Government will:

(i) draw up a cost-effective strategy for policy instruments to achieve the new national target,
(ii) allocate more funding for research into noise problems,
(iii) take an active part in the EUs work in this field.

Additionally, there is the Environment action plan for the transport sector (addendum 1999):

The goal of the transport authorities is to assist attainment of the new national noise pollution goal.
Furthermore, it is pointed out that there is a strong need for the development of tools for the actual determination of a numerical measure of the noise annoyance.

The problem of the determination of the noise annoyance has at least two important components. One of them is the specification of what ‘annoyance’ is, and it is for instance well established that different sources give rise to different degrees of annoyance. In the above Norwegian target it is decided to make use of the noise annoyance index (SPI) [12]. Another important component is the determination of the sound pressure input for the calculation of the annoyance.

HARMONOISE is an EU project within the Fifth Framework Program for the Harmonized Accurate and Reliable Methods for the EU Directive on the Assessment and Management Of Environmental Noise [32]. This project is planned to last three years and was initiated in 2002. One of their initial observations was that even though measurement appears to be more straightforward than calculation in the eyes of the general public, in most member states the standardized methods state a general preference for calculation as the way to assess environmental noise levels.

Seemingly straightforward measurement is in fact almost impossible in most cases of interest. The problem is mainly due to the large number of different sources, with a corresponding identification problem.

As an example it can be mentioned that SINTEF did an effort in the direction of measuring the noise exposure from a military training field in the nearby population. The measurements where dominated from noise from the population, and it was difficult to obtain the component of the noise from the military training field. It is probably more sensible to measure the noise near to the sources, followed by a calculation of the corresponding far-field exposure onto the population.

The situation is essentially the same for road vehicle noise, except that the identification problem is even more difficult.

A recent development with respect to noise prediction modeling was made in the Nordic countries; government funding from the Nordic council of Ministers provided for a significant improvement with respect to existing models in the EU. The Nord 2000 project for the development of new Nordic prediction methods for environmental noise, which started in 1996, presented the final results at a seminar in Copenhagen on September 27, 2001 [17]. The Nord 2000 project is described briefly by the following quotations from the HARMONOISE WEB pages [32, 2002]:

*The Nordic model will serve as the starting point for the work proposed in the HARMONOISE project. The new Nordic prediction methods consist of source modules for road and rail traffic and a sound propagation module. The source modules contain data on point source strength and source positions while the propagation module contains algorithms for calculating third octave band attenuation during transmission from source to receiver. The new propagation model is unique as a means for practical prediction in its foundation on physics, combining ray acoustic theory with diffraction theory. Such a model is superior to empirical models hitherto applied. Ray acoustic theory deals with the frequency dependent interaction between sound waves traveling along different paths between source and receiver. When a ray is diffracted the contribution to the sound field at the receiver is corrected for the diffraction.*
The background for the HARMONOISE project is given by the recent Directive 2002/49/EC of the European Parliament. According to the Directive the two noise indicators $L_{\text{den}}$ and $L_{\text{night}}$ will be used for strategic noise maps, and the calculation of these indicators is the overall aim in the development of new noise calculation methods [19, p.5]. The A-weighted long term average day-evening-night noise level $L_{\text{den}}$ is defined as

$$L_{\text{den}} = 10 \log_{10} \left( \frac{12}{24} 10^{L_{\text{day}}/10} + \frac{4}{24} 10^{(L_{\text{evening}}+5)/10} + \frac{8}{24} 10^{(L_{\text{night}}+10)/10} \right)$$

where $L_{\text{day}}$, $L_{\text{evening}}$, and $L_{\text{night}}$ are the A-weighted long term average noise levels for the day, evening, and night period, respectively. The day, evening and night period are periods of 12, 4, and 8 hours respectively. Which periods are considered day, evening and night will be defined by each Member State individually. The noise levels in each period are averaged over all meteorological variations and sound emission variations that occur throughout a representative year in that period.

From this it can conclude that the prediction of long term noise level faces the same problem as the prediction of the long term concentration of an air pollutant. In both cases the transmission depends on the atmospheric state which is highly variable. The local characteristics of meteorological variability is described by the meteorological parameters. This statistics (climatology) depends on the geographical and topographical situation. In mountainous and coastal areas the statistics is likely to vary even over short distances. The consideration of the local meteorological variability is even more important if a time correlation between the strength of emission and the state of the atmosphere exists. This is likely if the emission has a daily cycle (e.g. rush hour peaks) and the local climatology is determined to some degree by nightly inversions or thermally driven diurnal circulation systems such as slope winds, mountain and valley winds, or sea breezes.

One approach for the estimation of $L_{\text{den}}$ is to sample from the relevant distribution of the meteorological state, and also from the distribution of the source state.

An initial, and most important, problem is then to characterize the sources.

### 1.2 Vehicle noise

In 1930 J.S.Parkinson stated [16]:

The subject of vehicle noise is of interest for a variety of reasons. A very considerable part of the total noise observed both within buildings and in the streets is due to various types of transportation vehicles. The study of causes and remedies for vehicle noise therefore becomes of paramount interest in noise survey work.

He concludes:

There is need for further study in the field of vehicle noises. There is in particular need for thorough study of the noise produced by different makes of the same general type of vehicle.
Parkinson's statements, and the conclusion, are no less valid today. Vehicle noise is the dominant noise source and the motivation behind this report is the current need for more accurate methods for noise survey work.

The focus will be on the noise outside as the vehicle passes, and the approach is based on a model where the vehicle is represented generically as a collection of moving incoherent point sources. The main result is a method for the estimation of the individual source strengths based only on the observed sound exposure levels for a number of microphone positions. More sophisticated methods exist [6, 29], which demand more detailed measurements, e.g. pressure as function of time. These methods are certainly of great importance, for e.g. source height determination, but there is a need for an engineering method adapted to the needs of recently developed methods for use in noise survey work.

Statistical properties of the sound exposure from an ensemble of vehicles is an important part of the source characterization method. In a previous work, it was demonstrated that the choice of estimator for the vehicle sound power may be crucial, with a difference larger than 10 dB in parts of the one-third-octave spectrum [24]. This part of the spectrum is important for the total noise observed within buildings. The observation was quite surprising, and deserved further study [25]. The result is contained in the suggested method by the choice of estimator for the expected sound power of a population of vehicles.

There is basically two different estimation problems. One is given by a particular vehicle pass-by measurement and the other is given by an ensemble of vehicle measurements. Both cases are considered in this report.

The Nord2000 model [17][28] has been used extensively in the calculations, and by this it has also been demonstrated that this model is quite satisfactory for the purpose of sound exposure calculations from vehicle pass-bys if the source parameters are chosen properly.

### 1.3 Deterministic modeling of a road vehicle noise source

The basic assumptions in the road and rail traffic noise modules of Nord2000 [17] are as follows. A vehicle is represented as a moving array of incoherent point sources. Each point source $s$ is assigned a sound power $W_s$ for each of the 27 third octave bands from 25 Hz to 10 kHz. Additionally, there is a 3-dimensional directivity for each point source and each frequency band. A similar representation is likely to be a part of the engineering model developed in the EU HARMONOISE project [32].

In the following only one fixed frequency band is considered. The sound exposure at a microphone $m$ from a point source moving a short distance $\Delta x$ with speed $v$ is approximately $h W_s \Delta x / v$, where $h$ is a point-to-microphone transfer function for the given frequency band. The total sound exposure from a vehicle moving with constant speed and sound power on a curve can hence be written in the matrix form

$$E = CW,$$

where $E = (E_m), C = (C_{m,s}), W = (W_s)$, and
\[ E_m \quad \text{Sound exposure at microphone } m \]
\[ C_{m,s} \quad \text{Source-to-microphone transfer matrix} \]
\[ W_s \quad \text{Sound power of source } s \]

From the above it follows that the source-to-microphone transfer function has the speed dependence \( C(v) = C(v_0) v_0 / v \), and depends additionally on the frequency band, the geometry of the curve-terrain-microphone configuration, and additional sound propagation factors such as ground impedance and weather conditions.

The effect of directivity is included in \( C \), but if the directivity is speed dependent, then the simple speed dependence above is wrong.

The above is rather general, so it is fair to ask about limitations. The source-to-microphone transfer function argument above depends on a Riemann sum approximation and is valid quite generally given the existence of a point-to-microphone transfer function for the frequency band under consideration. The calculation in frequency bands is an approximation, but may in principle be made sufficiently accurate by a passage to narrow bands. The third octave representation is accurate only if the source signal and the propagation function are nearly constant within each third octave band. We remark here that the noise from the exhaust is tonal with distinct harmonics, but in the low frequency part of the spectrum. The noise from the tire-road-interaction is broadband, and dominates at not too low speeds. Third octave bands may hence be accurate enough despite the tonal character of parts of the vehicle noise, and this is supported by the experiments analyzed in this paper.

For numerical purposes it is possible to approximate both the integral over frequency and the integral over the curve with sufficient accuracy and this reduces the problem to the calculation of the sound exposure from a moving point source on a short segment with a given sound frequency. The speed will give a Doppler shift and will also influence the ground effect [22], [14, p.202-207], [21, p.698-737]. These effects are possible to include directly into the indicated numerical integrations, and are important for the calculation of the time history of the exposure and derived quantities such as the determination of maximum sound pressure levels. On the theoretical side the effect leads to the impossibility in principle of a transfer function representation as in equation (1.2) since a particular single frequency source with frequency \( f \) leads to non-zero sound exposure in the interval \((f, \infty)\) even though the source has no energy in this frequency interval. The theory may be repaired by a replacement of the multiplication in the frequency domain with convolution. The main contribution to the \( C \) source-to-microphone (convolution) transfer function for a straight road segment is however due to the configuration where the Doppler shift is close to zero, so it can be expected that the effect of the Doppler shift can be ignored in the calculation of the sound exposure from a vehicle pass-by. This conclusion is also supported by others [20]. The effect of the Doppler shift may be included approximately by the introduction of a speed dependent directivity. If the directivity is estimated directly from the time history of a vehicle pass-by, then the effect of the Doppler shift is automatically included.

The validity of the summation in the matrix product in equation (1.2) rests on the assumed incoherence between the sources. Clearly, the vehicle can be represented more accurately by coherent point sources, but corresponding calculations involving phase in addition to amplitude seems to be prohibitively time consuming and hence impossible for noise mapping purposes. The
effect of the presence of coherent point sources may be modeled to some extent by the directivity. Directivity is necessary in order to model the horn effect of the tire-road-interaction and the screening by the car body. In the following, we simply assume the validity of equation (1.2).

The total sound power $W$ of the vehicle (in the given frequency band) is the sum of the sound power from the individual sources and given by

$$W = \|W\|_1 = \sum w_s,$$

(1.3)

The point-source distribution is defined by

$$w = W/W$$

(1.4)

The calculation

$$E = CW = (C_w)W$$

motivates the definition

$$C = C_w$$

(1.5)

and gives a scalar version of equation (1.2)

$$E_m = C_m W$$

(1.6)

for each microphone $m$. The sound exposure $E_m$ at microphone $m$ is hence given by the sound power of the vehicle $W$ and the transfer function $C_m$ from the vehicle on the given curve to the position of microphone $m$. 
Chapter 2

The source-to-microphone transfer function

The source-to-microphone transfer function $C_{ms}$ corresponding to a vehicle test lane is defined such that

$$E_{ms} = C_{ms}W_s$$

(2.1)

is the sound exposure at microphone $m$ from the source $s$ in the model vehicle [27]. The purpose here is to investigate the dependence of $C_{ms}$ on various parameters defined in the suggested Nordtest method [27]. The calculations in the following are done with the Nord2000 method [28].

2.1 Height of microphone

The dependence of $C_{ms}$ on the height of the microphone is shown in Figure 2.1. The parameters chosen are typical for a road segment, and the distance corresponds in particular to a vehicle pass-by at 7.5 m when the axel width is 1.5 m. The selected heights are chosen from manual consideration of the 450 possible microphone heights at $(1, 2, \ldots, 450)$ cm.

The 15 cm height is approximately the microphone height where the ground effect is largest in the case considered, and in particular larger than the ground effect for the 1 cm microphone. Any microphone height in the interval $(11, 20)$ cm has a similar large ground effect.

The 150 cm height is approximately the microphone height where the ground effect is smallest in the case considered, and in particular smaller than the ground effect for the 300 cm and 400 cm microphones. Any microphone height in the interval $(141, 160)$ cm has essentially the same small ground effect, and almost so for the interval $(121, 180)$ cm. The ISO 362 [5] height 120 cm has almost the same small ground effect.

From this the microphone height $(150 \pm 20)$ cm is recommended for the measurement distance $d = 7.5$ m when the ground effect is to be minimized. The height $(15 \pm 5)$ cm is recommended when the ground effect is to be maximized.
Figure 2.1: Source-to-microphone transfer function for selected microphone heights for a 1 cm pass-by at 6.75 m.

The dependence of $C_{ms}$ on the height of the microphone for the vehicle distance 10 m is shown in Figure 2.2. A consideration similar to the above 450 possible microphone heights gives similar conclusions. In particular the microphone height $(205 \pm 30)$ cm is recommended for the measurement distance $d = 10$ m when the ground effect is to be minimized. The height $(15 \pm 5)$ cm is recommended when the ground effect is to be maximized.

Figure 2.3-2.4 show the dependence of $C_{ms}$ on the height of the microphone when the source height is 30 cm. The main observation is the interference minimum which moves to lower frequencies when the microphone height is increased. This is simply due to the increased path difference for the direct and reflected rays.

The microphone height 1 cm is seen to give the smallest ground effect if all possible source heights between 1 cm and 30 cm are considered. This conclusion depends however very much on the assumption of a plane road surface, and in practice this microphone height is not recommended except possibly for cases where the road surface is really even.

## 2.2 Distance from vehicle to microphone

The dependence of $C_{ms}$ on the distance $d$ of the microphone from the point source is shown in Figure 2.5. The parameters chosen are typical for a road segment, and the distance corresponds in particular to a vehicle pass-by when the axel width is 1.5 m. The selected distances are chosen from consideration of the distances that are useful in the suggested Nordtest method [27]. It follows in particular that an error of 10 cm in the distance gives an error which is less than 0.1
Figure 2.2: Source-to-microphone transfer function for selected microphone heights for a 1 cm pass-by at 9.25 m.

Figure 2.3: Source-to-microphone transfer function for selected microphone heights for a 30 cm pass-by at 6.75 m.
Figure 2.4: Source-to-microphone transfer function for selected microphone heights for a 30 cm pass-by at 9.25 m.

Figure 2.5: Source-to-microphone transfer function for selected microphone distances for a 1 cm pass-by for a microphone at height 2.05 m.
Figure 2.6: Source-to-microphone transfer function for selected road segment lengths for a 1 cm pass-by for a microphone at height 2.05 m.

dB. This error bound can be sharpened to 0.06 dB if the vehicle pass-by is at 10 m, and the error bound becomes even smaller for larger distances. This conclusion is also supported by manual consideration of the possible microphone distances at (650, 655, ..., 1500) cm.

2.3 Road segment length

The dependence of $C_{ms}$ on the left and right road segment lengths $l = r$ is shown in Figure 2.6. The parameters chosen are typical for a road segment, and the distance corresponds in particular to a vehicle pass-by when the axel width is 1.5 m. The selected distances are chosen from consideration of the distances that are useful in the suggested Nordtest method [27]. It follows in particular that an error of 10 m in the left road distance gives an error which is less than 0.5 dB for distances close to the recommended 30 m. This error bound can sharpened to 0.2 dB around $l = r = 70$ m, and is weakened to 0.8 dB around $l = r = 20$ m. This conclusion is supported by manual consideration of $l = r$ at (15, 16, ..., 75) m.

2.4 Speed of vehicle

The dependence of $C_{ms}$ on the vehicle speed is simply $C_{ms}(V) = C_{ms}(V_0)V_0/V$ if the point source have no speed dependent directivity. This dependence is shown in Figure 2.7. The parameters chosen are typical for a road segment, and the distance corresponds in particular to a
vehicle pass-by when the axel width is 1.5 m. The selected speeds are chosen from consideration of some typical and some extreme speeds that are useful in the suggested Nordtest method [27]. It follows in particular that an error of 5 km/h in the speed gives an error which is less than 3 dB for speed close to 10 km/h. This error bound can be sharpened to 1 dB around 20 km/h, to 0.5 dB around 40 km/h, and to 0.2 dB around 145 km/h. This conclusion is supported by manual consideration of speeds of (5, 10, ..., 150) km/h.

### 2.5 Temperature

The dependence of $C_{ma}$ on the air temperature is similar to the dependence on the microphone height. This can be explained by a shift in the interference minimum due to a shift in the wavelength from the shift in the sound speed. This dependence is shown in Figure 2.8. The parameters chosen are typical for a road segment, and the distance corresponds in particular to a vehicle pass-by when the axel width is 1.5 m. The selected temperatures are chosen from manual consideration of temperatures of $(-40, -39, \ldots, 50)$ Celsius. At $-40$ Celsius the ground effect is small. The ground effect increases with increasing temperature and reaches a maximum around 5 Celsius. The ground effect decrease when the temperature is further increased. The ground effect at 50 Celsius is similar to the ground effect at $-11$ Celsius.

It follows in particular that an error of 5 Celsius in the temperature gives an error which is less than 0.3 dB for temperature close to 20 Celsius.
Figure 2.8: Source-to-microphone transfer function for selected air temperatures for a 1 cm pass-by for a microphone at height 2.05 m.

### 2.6 Ground impedance

The dependence of $C_{ms}$ on the flow resistivity is similar to the dependence on the microphone height. The ground effect increase with decreasing flow resistivity which can be explained by a shift in the interference minimum towards lower frequencies for a decreasing flow resistivity. This dependence is shown in Figure 2.9. The parameters chosen are typical for a road segment, and the distance corresponds in particular to a vehicle pass-by when the axel width is 1.5 m. The selected flow resistivities are chosen from manual consideration of 20 selected flow resistivities in the range $2 kN\,sm^{-4}$ to $640 MN\,sm^{-4}$.

It follows in particular that a change from $2 MN\,sm^{-4}$ to $20 MN\,sm^{-4}$ gives a 1 dB change at 1 kHz and a 6 dB change at 10 kHz. This range of variation in the flow resistivity is found from for instance measurements on different seemingly equivalent roads in Trondheim.

### 2.7 The exposure level difference

The vehicle-to-microphone transfer function $C_m$ corresponding to a vehicle test lane is defined such that

$$E_m = C_m W$$  \hfill (2.2)
Figure 2.9: Source-to-microphone transfer function for selected flow resistivities for a 1 cm pass-by for a microphone at height 2.05 m.

is the sound exposure at microphone \( m \) from the vehicle in the model vehicle [27]. The suggested method is based partly on the dependence of the exposure level difference

\[
\Delta L_E := L_{E_1} - L_{E_2} = 10 \log \frac{C_1}{C_2}
\]

on various parameters defined in the suggested Nordtest method [27].

The idea is given by the second equality in equation (2.3). The right hand side is completely determined by the vehicle-to-microphone transfer functions for the two microphones and will be referred to as the theoretical exposure level difference. The left hand side is the exposure level difference and is directly measurable.

The idea of the level difference method is to adjust unknown parameters in the theoretical model such that the observed level difference becomes as close as possible to the theoretical difference. This is not a new idea [8] [10], but it is perhaps a slight novelty here to use it on the vehicle-to-microphone transfer function \( C_m \) instead of the point-to-microphone transfer functions [1].

A second observation is that each microphone gives an estimate

\[
W_m = E_m / C_m
\]

of the sound power \( W \). The minimalization of the difference between the observed level difference and the theoretical level difference is equivalent to a minimalization of the difference between the sound power level estimates, since

\[
L_{W_1} - L_{W_2} = (L_{E_1} - L_{E_2}) - 10 \log \frac{C_1}{C_2}
\]
This observation gives in particular natural generalizations of the level difference method to the case of more than two microphones [26].

The parameters of interest here are the flow resistivity $\sigma$ and the point-source-weight $w$. Extensive calculations have been done with the Nord2000 method [28] and have demonstrated, together with comparison with experiments, that the level difference method can be applied for determination of $\sigma$ and $w$.

It is possible to present Figures similar to the previous Figures, but with the level difference replacing the exposure level. The dependence of the level difference on $\sigma$ is in fact already well illustrated by Figure 2.9.

Variation of $\sigma$ correspond to a variation of the slope of the level difference for high frequencies.

Introduction of contributions from sources other than the low source give the possibility of introducing ”bumps” in the level difference, as indicated by Figure 2.4.

These two characteristic features of the level difference curves are also clearly visible in observed level differences, and explains why the suggested method is possible.
Chapter 3

Estimation based on a single vehicle pass-by

3.1 Elementary estimation of sound power

Consider a single vehicle pass-by and corresponding measurements of sound exposures in $m_{\text{max}}$ microphones. It is assumed that an acoustical model on the following form is given

$$E_m = C_m W$$  \hspace{1cm} (3.1)

where

- $E_m$: Sound exposure at microphone $m$
- $C_m$: Source-to-microphone transfer function for the vehicle
- $W$: Sound power of the vehicle, assumed to be constant

If the vehicle is modeled as an array of moving incoherent point sources, then a model on the form given by equation (3.1) holds. Equation (3.1) gives the estimator

$$W_m = E_m / C_m$$  \hspace{1cm} (3.2)

of the sound power from each microphone, and a possible estimator of $W$ is simply the arithmetic mean $\bar{W}$ of the individual estimates. This is however only one possible choice, and the problem of choosing the best estimator motivates further discussion.

One possible reason for deviations between the estimates is simply that the calculated transfer functions $C_m$ are erroneous due to failure of the assumed model. The model assumes in particular incoherence between the sources, approximates the Doppler effect, and approximates by calculation in a fixed frequency band. These assumptions are clearly principally wrong, and will certainly give deviations between the estimates, but these deviations will be assumed to be negligible in the following. This assumption is strongly supported by actual measurements when the Nord2000 model for point-to-point propagation is used.

More important than the principal difficulties in the model are certain choices of parameters in the model. A most important choice is the position of the point sources and the corresponding
point-source distribution \( w \). Another important choice is the modeling of the effect of the ground, and in particular the actual value of the impedance(s) \( Z \) of the ground. Horizontal and vertical directivity may also be important in some cases. Vertical directivity could be important if the maximum difference in vertical angle between the microphones is large. Horizontal directivity tends to be less important for a total pass-by exposure, but is certainly important if a short road segment is considered\(^1\). Depending on the actual measurement site\(^2\) there may be many other possible crucial parameters which determine the actual acoustical model.

Finally, and perhaps most importantly, there will be errors in the actual measured sound exposures. The microphones have intrinsic limitations on accuracy, and wind induced microphone noise and other irrelevant noise sources may be important.

### 3.2 Estimation of sound power with normally distributed errors

A reasonable statistical model for the measured sound exposures is given by

\[
E_m = C_m W + N_m,  \tag{3.3}
\]

where \( N_m \) represents the random errors in the measured sound exposure \( E_m \). More specifically it will be assumed that \( N_m \sim N(0, \sigma_m^2) \). Furthermore it is assumed that the errors in each microphone are statistically independent. It follows then that \( E_m \) are independent with a Gaussian distribution

\[
E_m \sim N(C_m W, \sigma_m^2)  \tag{3.4}
\]

The sound power \( W \) is not a random quantity here since only one particular vehicle is considered.

With this statistical model given there is a method which essentially gives a unique best estimator for the sound power, and hence the initial dilemma of choosing an estimator is solved. For the intended use of the estimated sound power for noise mapping purposes it is essential that the estimator is unbiased. The estimator

\[
\hat{W}_A = \frac{\sum_m (C_m/\sigma_m)^2 (E_m/C_m)}{\sum_m (C_m/\sigma_m)^2}  \tag{3.5}
\]

is unbiased: \( \mathbb{E} \hat{W}_A = W \). It is a weighted mean of the unbiased estimators from each microphone. The estimator has minimum variance since it is a function of the complete minimal sufficient statistic \( \sum_m (C_m/\sigma_m)^2 (E_m/C_m) \) for the parameter \( W \) [7, Theorem 6.1.6]. The UMVU estimator \( \hat{W}_A \) is also the maximum-likelihood estimator in this case, and hence also coincides with the least-squares solution of the system of equations \( E = CW \).

\(^1\)This gives a natural method for the estimation of directivity.

\(^2\)Including e.g. weather conditions, geometry, terrain, vehicle speed, etc
3.2.1 The accuracy of the estimator

The variance of $\hat{W}_A$ is

$$\text{Var} \hat{W}_A = 1/\sum_m (C_m/\sigma_m)^2$$  \hspace{1cm} (3.6)

It is hence preferable with a large $C_m$, which is intuitively obvious, but equation (3.6) gives a more precise numerical statement. This statement holds generally also if we do not assume normality, and in this case the estimator $\hat{W}_A$ is the best unbiased linear estimator. Equation (3.6) also gives precisely how the accuracy increase with an increasing number of microphones.

When $\hat{W}_A$ is used as an estimator for $W$, one can assert with the probability $1 - \alpha$ that the error $|\hat{W}_A - W|$ will not exceed

$$\Delta_A z = \frac{z_{\alpha/2}}{\sqrt{\sum_m (C_m/\sigma_m)^2}}$$  \hspace{1cm} (3.7)

where $z_\alpha$ is the $(1 - \alpha)100$ percentile of the standard normal distribution. The case $\alpha = 0.05$ corresponding to a 95% confidence interval gives in particular $z_{0.025} = 1.96$.

Unfortunately the variances $\sigma_m^2$ are in most cases unknown, and then equation (3.7) is of little use. If $\sigma_m = \sigma$, then the measurements can be used to estimate $\sigma$ as well. 3 The statistics $\sum_m E_m C_m$ and $\sum_m E_m^2$ are complete and sufficient statistics for the parameters $W$ and $\sigma^2$ by an application of the Halmos-Savage factorization theorem [13]. Let $m_{\text{max}}$ be the number of microphones, and define

$$S_A^2 = \frac{1}{m_{\text{max}} - 1} \sum_m (E_m - C_m \hat{W}_A)^2$$  \hspace{1cm} (3.8)

The statistic $(\hat{W}_A, S_A^2)$ is then an alternative sufficient statistic, and since the distribution of $S_A^2$ only depends on $\sigma$ it follows that $\hat{W}_A$ and $S_A^2$ are independent. This argument depends on the Basu theorem [7, p.262] and the completeness of the sufficient statistic $\hat{W}_A$ for the parameter $W$. A computation shows that $\mathbb{E} S_A^2 = \sigma^2$ and hence $S_A^2$ is the unique UMVU estimator for $\sigma^2$.

When $\hat{W}_A$ is used as an estimator for $W$, and $\sigma$ is unknown, one can assert with the probability $1 - \alpha$ that the error $|\hat{W}_A - W|$ will not exceed

$$\Delta_A = \frac{t_{\alpha/2}(m_{\text{max}} - 1)}{\sqrt{\sum_m C_m^2}} S_A$$  \hspace{1cm} (3.9)

where $t_\alpha(n)$ is the conventional $(1 - \alpha)100$ percentile of the Student’s t distribution with $n$ degrees of freedom 4. The $\alpha = 0.05$ corresponding to a 95% confidence interval gives in particular $t_{0.025}(1) = 12.71$, $t_{0.025}(2) = 4.30$, and $t_{0.025}(3) = 3.18$ for the cases of two, three, or four microphones respectively.

---

3The more general case $\sigma_m = \gamma_m \sigma^2$ with $\gamma_m$ known can be transformed and handled by the same argument.

4This definition deviates from the choice by ISO 3534 [4, Part 1, p.42], which uses the symbol $t_\alpha(n)$ to denote the $\alpha$100 percentile. The ISO definition deviates from common use in statistics [7, p.415].
The proof of the exactness of the preceding confidence interval follows from inversion of the pivotal quantity

\[
\frac{\hat{W}_A - W}{S_A/\sqrt{\sum_m C^2_m}} \sim t(m_{\text{max}} - 1)
\]

and its distribution. The distribution statement follows since the left-hand side of equation (3.10) equals a standard Gaussian variable divided by \(\sqrt{S_A^2/\sigma^2}\), and \(S_A^2/\sigma^2 \sim \chi^2_{m_{\text{max}} - 1}/(m_{\text{max}} - 1)\). This last statement follows from

\[
\sigma^{-2} \sum (E_m - C_m W)^2 - \sigma^{-2} \sum (E_m - C_m \hat{W}_A)^2 = \sigma^{-2} \sum C^2_m (\hat{W}_A - W)^2
\]

where the first sum is \(\chi^2_{m_{\text{max}}}\) and the last sum is \(\chi^2_1\). The confidence intervals corresponding to equations (3.7) and (3.9) reduce to the classical results in the case \(C_m = 1\) for all \(m\). The completely general matrix case is treated by Rao [23, p.238, equation (4b.1.6)], and the result here is a special case.

The assumed independence in the model given by equation (3.3) is reasonable if the random error is due to the limited accuracy of the microphones. If, however, the random error is due to variations in the ambient noise, or due to wind induced noise at the microphones, then independence is far from reasonable. These sources of error can also be modeled statistically, but this will not be analyzed in any detail here. The simplest model is to consider the given vehicle pass-by and the ambient conditions as given, and the additional error terms are then simply constants for each microphone. This is similar to errors in the \(C_m\)'s, and the net result of both is a bias of the estimator \(\hat{W}_A\).

### 3.3 Estimation of sound power with log-normal errors

The model given by equation (3.3) is convenient, but there are other possible models which are equally reasonable. A particularly reasonable alternative is given by

\[
L_{E_m} = L_{C_m} + L_W + N
\]

where

- \(L_{E_m}\) Sound exposure level at microphone \(m\), \(L_{E_m} = 10 \log_{10}(E_m)\)
- \(L_W\) Sound power level of vehicle, \(L_W = 10 \log_{10}(W)\)
- \(L_{C_m}\) Level transfer function of vehicle, \(L_{C_m} = 10 \log_{10}(C_m)\)
- \(N\) measurement error, \(N \sim N(0, \sigma^2)\)

The above dimensionless \(E_m, W, C_m\) are defined by \(E_m = E_m^*/p_0^2t_0\), \(W = W^*/W_0\), and \(C_m = C_m^*W_0/p_0^2t_0\), where \(p_0 = 20 \mu Pa, t_0 = 1s, W_0 = 20 \mu Pa, t_0 = 1s\), and the stared symbols denote the conventional dimensional quantities. All of the above analysis for the previous model can be applied verbatim based on the statistic

\[
Z_m = L_{W_m} = L_{E_m} - L_{C_m} \sim N(L_W, \sigma^2)
\]

\footnote{A quantity \(\phi(T, \theta)\) is pivotal for the parameter \(\theta\) if the distribution of the quantity have no dependence on the parameter.}
The maximum-likelihood estimator $\tilde{W}$ for $W$ is given by

$$L_{\tilde{W}} = Z \sim N(L_W, \sigma^2/m_{\max})$$  \hspace{1cm} (3.14)$$

This estimator is also the least-squares solution of $L_E = L_W + L_C$, but is unfortunately biased

$$E\tilde{W} = W 10^{0.1[0.05 \ln(10)\sigma^2/m_{\max}] \neq W}$$  \hspace{1cm} (3.15)$$

The arithmetic mean estimator $\bar{W}$ is even more biased in this model, since

$$E\bar{W} = E W_m = W 10^{0.1[0.05 \ln(10)\sigma^2]} \neq W$$  \hspace{1cm} (3.16)$$

and the same bias is obtained from any weighted average. The estimator $\tilde{W}$ is the geometric average, and this gives $\tilde{W} \leq \bar{W}$.

It is not completely elementary to obtain an unbiased estimator for $W$ in this log-normal model. The estimand is in this case given by

$$W = e^{0.1 \ln(10)L_W}$$  \hspace{1cm} (3.17)$$

which can be identified with $\theta_{a,b,c}$ [9, p.28-31] [25] with $a = 0.1 \ln 10$, $b = c = 0$. The unique UMVU estimator of $W$ is then

$$\hat{W}_B = 10^{0.1Z} {}_0F_1\left(\frac{m_{\max} - 1}{2}, -\frac{(0.1 \ln 10)^2(m_{\max} - 1)}{4m_{\max}}S_B\right)$$  \hspace{1cm} (3.18)$$

where

$$\begin{align*}
{}_0F_1(\alpha; z) &= \sum_{j=0}^{\infty} \frac{z^j}{j!(\alpha)_j} \\
(\alpha)_j &= \frac{\Gamma(\alpha + j)}{\Gamma(\alpha)} \\
\Gamma(z) &= \frac{\Gamma(z + 1)}{z}
\end{align*}$$  \hspace{1cm} (3.19)$$

and $\Gamma$ is the gamma function. The generalized hypergeometric function ${}_0F_1$ is an entire function [11, Vol. 1, p.182], and in the particular application here the corresponding series is in addition alternating. Generally the estimator $\hat{W}_B$ may take negative values. This is rather unfortunate, but should not cause any problems for the case at hand. The estimate is positive if $S_B < 75 < 4/(0.1 \ln 10)^2$. The result given by equation (3.18) follows from the theory of the log-normal distribution [9, p.28-31].

### 3.3.1 The accuracy of the estimator

The error $|L_{\hat{W}_B} - L_W|$ will not exceed

$$\Delta_B = \frac{t_{\alpha/2}(m_{\max} - 1)}{\sqrt{m_{\max}}} S_B$$  \hspace{1cm} (3.20)$$
where \( t_\alpha(n) \) is the conventional \((1 - \alpha)100\) percentile of the Student’s t distribution with \( n \) degrees of freedom, and

\[
S_B^2 = (m_{\text{max}} - 1)^{-1} \sum m (L_{E_m} - L_{C_m} - L_{\tilde{W}_B})^2
\]  

(3.21)

The corresponding \((1 - \alpha)\) confidence interval for \( W \) is

\[
[\tilde{W}_B10^{-0.1\Delta_B}, \tilde{W}_B10^{0.1\Delta_B}],
\]  

(3.22)

where

\[
\tilde{W}_B := 10^{0.1L_{\tilde{W}_B}}
\]  

(3.23)
Chapter 4

Estimation of the mean sound power of a population of vehicles

The sound power of the road vehicles is the most important quantity in sound mapping calculations. Here it is explained initially that a statistical model is needed, and then the estimation problem is considered. The presentation here complements parts of a previous report on the same subject [25].

4.1 The sound exposure from a road segment

The sound exposure $E$ at a fixed position from a vehicle $S$ driving at constant speed $V$ over fixed road segment is assumed to be given on the form

$$E = CW$$  \hspace{1cm} (4.1)

where $C$ is the transfer function corresponding to the given geometry, and other parameters. For a given category of vehicles, and given parameters such as vehicle speed and road surface temperature, the transfer function $C$ is determined. This is indeed one reason for the introduction of vehicle categories.

The sound power $W$ is however not determined since the variation from one vehicle to the next is large. It will be assumed that the distribution of $W$ is fixed by the given category and given parameters. The distribution is to be found from measurements of sound exposure from vehicle pass-bys.

The most important parameter to determine is the expected sound power $E(W)$. It follows from equation (4.1), and assumed incoherence between various sources, that unbiased estimation of the expected sound exposure follows from unbiased estimation of the expected sound power. A main aim is hence unbiased estimation of the expected sound power.

The speed $V$ of the vehicle is of particular importance in the determination of the sound exposure since the time interval of the exposure is given by the length of the road segment divided by $V$. 

The probability distribution of $V$ will depend on the signed speed limit, the category of road, weather conditions, and possibly other parameters. For a given road segment, a given category of vehicle, and possibly other parameters, the distribution of $V$ is fixed. The determination of this distribution can be done quite independently of the acoustic characterization, and it will be assumed that the distribution of $V$ is known. The expected exposure, and how the distribution of $V$ enter the calculation is given by a double expectation

\[
\mathbb{E}(E) = \mathbb{E}[\mathbb{E}(CW \mid V)] = \mathbb{E}[C \mathbb{E}(W \mid V)]
\] (4.2)

The last equality holds since it is assumed the $C$ is a constant when the speed is given. It follows that an unbiased estimator of the expected sound exposure is given if we can find an unbiased estimator of the conditional expected sound power for each speed.

Similar arguments are equally valid for other parameters such as the road surface temperature. The special feature of $V$ is however that $CV$ is a quantity that does not depend on $V$ in many models for road vehicle noise, since it is in particular true for a moving point source with a speed independent directivity. Besides the directivity it is also quite possible that the point source distribution depends on $V$. Given that $CV$ has no speed dependence, the following holds

\[
\mathbb{E}(E) = CVQ
\] (4.3)

where

\[
Q = \mathbb{E}[\mathbb{E}(W \mid V)/V] = \mathbb{E}(W/V)
\] (4.4)

This expected value is an integration over the variation from vehicle to vehicle in a given category, including the variation in speed on the given road segment. The quantity $Q$ is the expected sound energy per distance road. A big advantage with the introduction of $Q$ is that the averaging over $V$ can be done once and for all, independent of the given microphone position. In the general case the averaging over $V$ in the expectation $\mathbb{E}(CW)$ must be done separately for each receiver position.

Let $N$ be the number of vehicles of the given category passing the road segment in a specified time interval, e.g. a given hour in a year. The expected sound exposure from these vehicles is

\[
\mathbb{E}\left(\sum_{i=1}^{N} E_i\right) = \mathbb{E}(N) \mathbb{E}(E_i)
\] (4.5)

if $N$ is statistically independent of the exposure $E_i$ for each vehicle $i$. The exposure $\mathbb{E} E_i$ is independent of $i$ since all vehicles are in the same category. The distribution of $N$, and in particular the expected number of vehicles $\mathbb{E}(N)$, can be estimated independently of the acoustic characterization. This is similar to the case of the speed distribution $V$ and essentially $\mathbb{E}(N)$ can be considered to be known.

Generally in the estimation of a yearly $L_{den}$ there must also be an averaging over the variations in the weather conditions. Since both the sound propagation and the source strength, including expected number of vehicles, depends on the weather conditions this averaging must be done as the final step in the calculation. All of the above should hence be interpreted as conditional on the weather conditions.
4.2 Expected sound power

Let $W_i$ be estimated sound power of vehicle $i$. Assume that the error in each estimate is negligible compared to the variation in sound power from vehicle to vehicle, so it can be assumed that $W_i$ is a random sample from the distribution of $W$. The estimator

$$\bar{W} = (W_1 + \cdots + W_n)/n$$

(4.6)

is unbiased for $\mathbb{E} W$ regardless of the distribution of $W$. If $n$ is large, then this estimator can be a good choice, but generally the variance of this estimator is unnecessarily large. A better estimator follows if a parametric model holds. The log-normal distribution is certainly convenient, and seems moreover to be supported by measurements [24].

It will be assumed that

$$L_W \sim N(\mu, \sigma^2)$$

(4.7)

The validity of this assumption will certainly depend on the vehicle category, the frequency band under consideration, the vehicle speed, the driving conditions, and possibly other parameters. The quantity to be estimated is

$$\mathbb{E} W = 10^{0.1[\mu + 0.05 \ln(10) \cdot \sigma^2]}$$

(4.8)

This gives the alternative estimator

$$\hat{W} = 10^{0.1[\hat{\mu} + 0.05 \ln(10) \cdot \hat{\sigma}^2]}$$

(4.9)

where

$$\hat{\mu} = \bar{L}_W = (L_{W_1} + \cdots + L_{W_n})/n$$

(4.10)

$$\hat{\sigma}^2 = \frac{n}{n-1} (L_W - \hat{\mu})^2$$

(4.11)

are the standard unbiased estimators of $\mu$ and $\sigma^2$.

Except for the factor $n/(n-1)$ in the definition of $\hat{\sigma}^2$ the estimator $\hat{W}$ is the maximum-likelihood estimator for $\mathbb{E} W$. The estimator $\hat{W}$ is based on the minimal sufficient statistic and is hence typically more precise than the estimator $\bar{W}$. It is unfortunately not unbiased.

The UMVU estimator for $\mathbb{E} W$ is

$$\tilde{W} = 10^{0.1\hat{\mu}} \cdot F_1\left(\frac{n-1}{2}, (0.1 \ln 10)^2 \frac{(n-1)^2}{4n} \hat{\sigma}^2\right)$$

(4.12)

where $F_1$ is defined in equation (3.19). The result given by equation (4.12) follows from the theory of the log-normal distribution as before for equation (3.18) [9, p.28-31].

Determination of exact confidence intervals for $\mathbb{E} W$ is more complicated, but UMA unbiased level $1 - \alpha$ confidence sets can be constructed [9, Chap.3]. The confidence set is however not necessarily an interval, and an alternative more recent procedure will be presented here.

Monotonicity implies that confidence intervals for $\mathbb{E} W$ follows from confidence intervals for $\mu + 0.05 \ln(10) \cdot \sigma^2$. Confidence intervals for $\mu + \sigma^2/2$ are derived in [18, p.108], and can be
generalized by scaling to include general linear combinations of $\mu$ and $\sigma^2$. A $(1 - \alpha)$ confidence interval for $\mathbb{E}W$ is given by

$$10^{0.1\cdot(\hat{\mu} - c_{\alpha/2} \hat{\sigma} \sqrt{(n-1)/n})}, \quad 10^{0.1\cdot(\hat{\mu} + c_{1-\alpha/2} \hat{\sigma} \sqrt{(n-1)/n})}$$

where $c_{\alpha}(\hat{\sigma}, n)$ is the $\alpha100$ percentile of the variable

$$Z = \frac{\ln(10) \hat{\sigma} \sqrt{n(n-1)}}{20U^2}$$

where $Z \sim N(0, 1)$ and $U^2 \sim \chi^2_{n-1}$ are independent variables. The percentile can be calculated accurately by Monte Carlo simulation [18, p.108].

An alternative and seemingly accurate procedure based on a modified signed log-likelihood ratio is presented by Wu, Wong, and Jiang [33, p.1853].

### 4.3 Expected sound power given the speed

The speed distribution of the vehicles on a given road segment is important in noise mapping calculations. To calculate the expected emission from a segment one must in principle average over the speed distribution, and then the expected sound power given the speed is needed.

In the previous section there was no reference to the speed, but one approach for the estimation of $\mathbb{E}(W \mid V = v)$ is to use the indicated method for all vehicles with speed limited by $v \pm \Delta v$. This is reasonable if there is no obvious speed dependence, and if $\Delta v$ is sufficiently small it will be reasonable in any case since the variation from vehicle to vehicle will dominate. This reasoning with $\Delta v = 2.5$ km/h is used by Jonasson [15, p.56], and is also the choice in the suggested method here. The reason is mainly that it simplifies the formulation of the method.

For low frequencies (e.g. below 200 Hz) the suggested method is reasonable, since this will be mainly engine noise and the speed is then not the most important parameter. For frequencies around 1 kHz it is however well known that the sound power increase with speed, which is reasonable as the noise is mainly caused by the tire-road interaction.

In the present Nordic prediction model the A-weighted sound exposure at 10 m for a light vehicle pass-by is correspondingly given by [3, Part I: p.8 and Part II: p.9]

$$L_E = A + B \log\left(\frac{v}{v_0}\right), \quad v \geq v_{\text{min}}$$

where

- $A$ equals 73.5 for light vehicles and 80.5 for heavy vehicles
- $B$ equals 25 for light vehicles and 30 for heavy vehicles
- $v$ is the measured average speed, if known, else posted speed
- $v_0$ equals 50 km/h
- $v_{\text{min}}$ equals 40 km/h for light vehicles and 50 km/h for heavy vehicles

$^1$The engine speed and gear is more important. Regression on these parameters may then be reasonable.
The exposure is assumed to be constant below $v_{\text{min}}$. This is reasonable according to the previous argument since the engine noise will dominate at low speed. In the case of heavy vehicles the model is formulated only for $v \leq 90$ km/h.

The previous motivates the model

$$(L_W \mid V = v) \sim N(\mu, \sigma^2), \quad \mu = A + B \lg\left(\frac{v}{v_0}\right)$$  \hspace{1cm} (4.16)$$

This is a generalization of the model given in equation (4.7) since the model involves an additional parameter $B$. The previous model is obtained with $B = 0$, which gives $\mu = A$. The introduction of the unknown parameter $B$ will give larger uncertainty in the estimates, but this can hopefully be compensated by the allowance of a larger speed interval with a corresponding larger number of observations. The speed in equation (4.26) is the actual speed, and should not be confused with the average speed as in the formulation of the present Nordic model [3, Part I: p.8 and Part II: p.9].

The least squares estimators of $A$ and $B$ are

$$\hat{A} = \overline{L_W} - \hat{B} \lg\left(\frac{v}{v_0}\right)$$  \hspace{1cm} (4.17)$$

$$\hat{B} = \frac{(L_W - \overline{L_W})(\lg\left(\frac{v}{v_0}\right) - \overline{\lg\left(\frac{v}{v_0}\right)})}{(L_W - \overline{L_W})^2}$$  \hspace{1cm} (4.18)$$

and these estimators are also the best linear unbiased estimators under more general statistical models [7, p.560]. Unbiased estimators of $\mu$ and $\sigma^2$ are given by [7, p.569, p.575]

$$\hat{\mu}_i = \hat{A} + \hat{B} \lg\left(\frac{v_i}{v_0}\right) \sim N(\mu_i, \lambda_i^2 \sigma^2)$$  \hspace{1cm} (4.19)$$

$$S^2 = \frac{1}{n-2} \sum_i (L_{W_i} - \hat{\mu}_i)^2 \sim \frac{\sigma^2}{n-2} \chi^2_{n-2}$$  \hspace{1cm} (4.20)$$

where

$$\lambda_i^2 = \frac{1}{n} \left[ 1 + \frac{(\lg\left(\frac{v_i}{v_0}\right) - \overline{\lg\left(\frac{v}{v_0}\right)})^2}{(\lg\left(\frac{v_i}{v_0}\right) - \overline{\lg\left(\frac{v}{v_0}\right)})^2} \right]$$  \hspace{1cm} (4.21)$$

The estimators $\hat{\mu}_i$ and $S^2$ are independent [7, p.569] and a complete sufficient statistic for $\mu_i, \sigma^2$. This holds for an arbitrary speed, and not only for each observed speed $v_i$. A reasonable estimator for $E(W \mid V = v)$ is now

$$\hat{W} = 10^{0.1[\hat{\mu} + 0.05 \ln(10) - S^2]}$$  \hspace{1cm} (4.22)$$

but unfortunately this estimator is biased just as the analogous estimator given in equation (4.9). A generalization of the proof given by Shimizu [9, p.30] gives the UMVU estimator

$$\hat{W} = 10^{0.1\hat{\mu} \_F_1\left(\frac{n-2}{2}, (0.1 \ln 10)^2 \frac{(n-2)(1-\lambda^2)}{4} S^2\right)}$$  \hspace{1cm} (4.23)$$

It should be noted that in this case there is no obvious unbiased estimator for $E(W \mid V = v)$ as in equation (4.6).
A \((1 - \alpha)\) confidence interval for \(\mathbb{E}(W \mid V = v)\) is given by a generalization of [18, p.108],

\[
10^{0.1 \left[ \hat{\mu} - c_{\alpha/2} S \sqrt{(n-2)\lambda^2} - \hat{\mu} + c_{1-\alpha/2} S \sqrt{(n-2)\lambda^2} \right]}
\]

where \(c_\alpha(\hat{\sigma}, n)\) is the \(\alpha100\) percentile of the variable

\[
\frac{Z}{U} + \frac{\ln(10) \hat{\sigma} \sqrt{(n-2)/\lambda^2}}{20U^2}
\]

where \(Z \sim N(0, 1)\) and \(U^2 \sim \chi^2_{n-2}\) are independent variables. The percentile can be calculated accurately by Monte Carlo simulation [18, p.108].

This gives a confidence interval for each speed, but not a confidence band with simultaneous limit curves for all speeds. Confidence bands for \(\mu(v)\) follows from standard theory [7, p.577-], but confidence bands for \(\mathbb{E}(W \mid V = v)\) seems more difficult to obtain.

In the previous it was assumed that there was no error in the observed speed. If there is a non-negligible error in the observed speed the analysis is much more complicated. With additional, possibly rather ad hoc assumptions relating the error in speed with the error in observed level, the analysis leads to an orthogonal least squares solution for the estimation of \(\mu\) [7, p.587]. It seems difficult to obtain confidence intervals for \(\mathbb{E}(W \mid V = v)\). It is even difficult to obtain confidence intervals for \(\mu\) in this more general measurement error model [7, p.582, p.592].

### 4.4 Expected sound energy per distance road

As explained prior to equation (4.4) it can be advantageous to characterize the noise source strength by the quantity \(Q = \mathbb{E}(W/V)\), which is the sound energy per distance road. The most elementary unbiased estimator of \(Q\) is

\[
\overline{Q} = (W_1/V_1 + \cdots + W_n/V_n)/n,
\]

but as in the previous this may be to unprecise. A parametric model could be assumed, and then an improved estimator would be possible, for instance guided by the sufficiency principle. A related approach would be to derive the distribution from the conditional distribution of \(W\) given \(V = v\) and the distribution of \(V\). This seems advantageous since the determination of the distribution of \(V\) is a problem which is more elementary, and can be solved independently of the noise mapping problem. If it is assumed that the distribution of \(V\) is given, then the previous section gives the following unbiased estimator

\[
\hat{Q} = \int \tilde{W}(v) v^{-1} P_V(dv)
\]

This seems to be a reasonable choice, in particular when \(P_V\) has been derived by a large number of measurements of the speed. The integral in equation (4.27) can be cumbersome to evaluate directly, and one approach is the Monte-Carlo estimator

\[
\hat{Q} = (\tilde{W}(V_1)V_1^{-1} + \cdots + \tilde{W}(V_n)V_n^{-1})/n
\]
One advantage with this is that it is not necessary to estimate $P_V$ first, but one can simply use observed values for the speed. On the other hand, if a good parametric model for the distribution of $V$ is known, then this should be used for the estimation of $P_V$, and then one can use equation (4.28) with a very large simulated sample from $P_V$. This will typically reduce the variance, since the variance from the distribution of $V$ will be effectively removed.

This can also be used as an example of how additional averaging can be done. For the case of weather conditions the $\tilde{W}(v)$ must be replaced by $[C\tilde{W}](m)^2$, since both the source and the propagation depends on the meteorological state $m$. In this case actual integration seems unlikely, but a Monte-Carlo approach is possible.

Confidence intervals corresponding to the estimator given by the integral in equation (4.27) follows from confidence bands for $E(W | V = v)$, and can be taken as a motivation for the establishment of confidence bands. In particular since this will be useful more generally.

\footnote{Or possibly $CV Q$, to avoid averaging over $V$ for each source-receiver combination.}
Chapter 5

Discussion and conclusions

5.1 Complexity

A natural objection against the suggested method is that it is too complicated.

This unfortunate impression may partly be due to the rather long list of definitions. Most of the definitions are almost obvious, but needed due to the specification of the file formats for the results. This should hence not be a major obstacle.

The measurements needed are essentially identical to the measurements needed in the related method NT ACOU 109 [2]. Thus the measurement part should also be no major obstacle.

The most important difference between the suggested method and NT ACOU 109 is the processing of the data, and the corresponding reward is estimation of more estimands including in particular estimates of the uncertainty of the obtained results.

The processing of the data can, and should, be implemented in specialized software. Many of the rather detailed specifications in the method is intended to be sufficiently precise for unambiguous implementation in software. With this done the method should be quite straightforward to apply since the complexity is hidden by the software.

Software is anyway needed for the calculation of the curve to microphone transfer functions, and this is specified as part of the equipment needed.

The unfortunate complexity of the method seems unavoidable due to the corresponding complexity of the models intended for noise mapping purposes.

5.2 Flow resistivity

Figure 2.9 demonstrate the importance of the flow resistivity. The use of a wrong flow resistivity may give a 1 dB error in the 1 kHz band in the estimated sound power. The error increase rapidly
with increasing frequency. Below 250 Hz the road surface impedance is less important.

The flow resistivity is hence important for the estimation of the most important noise source, namely the tyre-road noise source. The flow resistivity is less important for the estimation of the engine noise.

A secondary effect of the road impedance is the effect on the multiple reflections between vehicle and road surface. This effect is included in the estimation of the sound power since the modeling of the engine noise is through a fictitious source. The vehicle model source represent the net effect of the real sources and the detailed geometry and material properties near the real sources.

The previous implies that a wrong flow resistivity will give a corresponding wrong estimate of the sound power. For calculation of the exposure from the vehicle at larger distances the effect increases since the reflection is almost at grazing incidence.

There is hence two aspects of a wrong flow resistivity. The first is that it influences the estimation of the sound power. The second is that it influences later noise mapping calculations.

The method suggested for the estimation of the flow resistivity is in principle very similar to the level difference method used in e.g. NT ACOU 104 [1].

One difference is that it uses the curve to point transfer function in stead of the point to point transfer function. This seems actually to be an advantage since it implies averaging over more point to point measurements.

The most important difference is that the source geometry is unknown. This could in principle ruin the suggested method, but fortunately the tyre-road source is sufficiently well defined in space. Minimalization of the total level error has been demonstrated to be practical, and the results agree with corresponding measurement with NT ACOU 104.

The expanded uncertainty is estimated in each application of the method and will depend on the number of pass-by measurements and the site. The accuracy is comparable with the accuracy of NT ACOU 104, and can typically be one-octave or better.

In the method it is required to measure the flow resistivity with a separate method. This can be done quite easily and should hence not be any major obstacle for the usage of the method. In cases where there is only one kind of ground surface at the site it is quite possible that this direct measurement will turn out to be unnecessary since the method itself gives a flow resistivity estimate. This can only be decided after a more thorough testing of the method in the field.

5.3 Weight

Figures 2.1-2.2 for a 1 cm pass-by can be compared with the corresponding 30 cm pass-bys in Figures 2.3-2.4. The main observation is the interference minimum which moves to lower frequencies when the source height is increased. This is simply due to the increased path difference for the direct and reflected rays, and this effect is larger for the 7.5 m pass-by than for the 10 m pass-by.
Unfortunately the choice of 7.5 m distance can not be recommended despite of this simply because the model assumptions become dubious at closer ranges. The model is intended for much larger distances in noise mapping calculations.

The effect of the weight is to give a result between the single source pass-bys for the heights in the model. The difference between the 1 cm and the 30 cm pass-bys can be as large as 10 dB in the 1 kHz band, so the choice of the weight and source heights are clearly important.

This large difference, when compared to measurements, gives actually a most convincing argument for the choice of a 1 cm source for the tyre-road noise. This has been the result in all tests of initial formulations of the method.

The difference is amplified by the presence of screens. This means in particular that a correct planning and construction of noise barriers are very much dependent on a good model for the position and weight of the sub-sources. The current Nordic model is based on an assumed source height equal to 0.5 m, and there is little doubt about the error in this assumption.

Below 250 Hz the weight is less important. In the method this will be reflected by corresponding large estimated uncertainty below 250 Hz. For noise mapping purposes this uncertainty is of no importance since the uncertainty in the calculated exposure will be unaffected by this large uncertainty.

A further discussion of the method for determination of the weight follows mainly the previous discussion for the determination of the flow resistivity. This is because the main idea is the same, namely the comparison of theoretical and measured level differences.

In the method the flow resistivity is estimated before the weight. This is because the flow resistivity is just a single number and the result of the estimation of the weight depends on the flow resistivity used.

The two estimation procedures can in principle be iterated, but the change in the estimate is expected to be small in most cases. This is because the estimation of the flow resistivity mainly depend on the fall-off of the level difference for high frequencies.

The most important conclusion is that actual measurements and testing of versions of the suggested method have demonstrated that it is possible to estimate the weight as suggested.

The second most important conclusion is that the method also gives an estimate of the accuracy of the result.

5.4 Source localization

The estimation of the weight depends on a priori information on the localization of the sources. Localization of the sources can be established by other methods, e.g. with acoustic imaging techniques, but the suggested method can also in principle be used since an arbitrary number of microphones is an included possibility.
A natural suggestion would be to choose model sources at heights 0.5, 1, 2, 3, 4, 5, 10, 15, 30, 35, 40, 45, 50 cm’s and do a number of pass-by measurements with at least 15 microphones as indicated in the TNO measurements in the TRL report [31, Fig.9].

It is possible that the gain in robustness in the suggested method outweighs the loss of initial information given by neglect of the phase of the sound pressure signal. This should be investigated further.

5.5 Sound power

The sound power of road vehicles is the single most important factor in noise mapping calculations. Road vehicles are well recognized to be the dominant source and a very accurate and sophisticated propagation model can not rectify errors in the source strengths. Furthermore, the sources contribute to many receiver points, but failure of the propagation model for difficult cases will typically only occur for special source-receiver configurations.

The figures in Chapter 2 give the dependence on single vehicle estimates of the sound power on errors in some of the most important model parameters. An overall conclusion is that the accuracy is sufficient for the ignorance of these errors compared to the variations in sound power from one vehicle to the next. This is important since it justifies a statistical model where the individual vehicle estimates is treated as if sampled from the distribution of the sound power from the population of vehicles.

An important aspect of the suggested method is the explicit formulation of a statistical model for the sound power. Based on this model an optimal estimator follow, and the estimator suggested in the method is a very good approximation of this estimator [25].

The model is perhaps the most convenient choice possible and most likely quite robust against model deviations, since it is based on the normal distribution. The model has been shown to be reasonable based on a limited set experiments [24]. Due to both lack of sufficient experimental material and time the validity of the assumption has not been sufficiently verified, and this should be investigated further.

The suggested estimator is unbiased, but more accurate biased estimators are known to exist. In this particular problem it is not a good idea to allow a small bias and in return get improved accuracy. The reason is the intended use of the estimate in the estimation of sound exposure, where the bias will multiply in the final sound exposure estimate.

The one single main result of the presented work is hence the method for the estimation of the expected sound power. The accuracy is estimated in each case and will depend on the number of vehicles and the quality of the measurement.
5.6 Conclusions

A method for the determination of source parameters for estimation of road vehicle noise has been developed. The main parts of the method have been tested with measurements and this verifies that the method can be used in practice. The method, as finally formulated, has not been tested, and this should be done in a Round-Robin test. Despite this, it is recommended to forward the method suggestion to the International Organization for Standardization (ISO). This is due to the lack of a corresponding method and the current need for the method within the EU. The method is needed in view of the development of new noise mapping methods (HARMONOISE) with background in the recent EU noise directive.

The method estimates the expected value of the sound power of a population of vehicles. Furthermore the method estimates the weight of the sub-sources in the vehicle model and the ground impedance of the road surface.

The method is based on statistical modeling and gives in particular estimates of the expanded uncertainty (ISO GUM) for all of the above mentioned parameters.

The report gives, together with two previous reports [SINTEF Report STF40 A02050, SINTEF Report STF40 A03063], the background for the suggested method.
Bibliography


Appendix A: NT ACOU 116

The approved methods NT ACOU 116 Road vehicles: Determination of noise emission, can be downloaded at www.nordicinnovation.net.
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