Int J Life Cycle Assess (2009) 14:676–686
DOI 10.1007/s11367-009-0117-1

METHODOLOGY • NOISE

Traffic noise in LCA

Part 2: Analysis of existing methods and proposition of a new framework for consistent, context-sensitive LCI modeling of road transport noise emission

Hans-Jörg Althaus · Peter de Haan · Roland W. Scholz

Received: 27 November 2008 / Accepted: 14 May 2009 / Published online: 11 August 2009
© Springer-Verlag 2009

Abstract
Background, aim, and scope An inclusion of traffic noise effects could change considerably the overall results of many life cycle assessment (LCA) studies. However, at present, noise effects are usually not considered in LCA studies, mainly because the existing methods for their inclusion do not fulfill the requirement profile. Two methods proposed so far seem suitable for inclusion in generic life cycle inventory (LCI) databases, and a third allows for inter-modal comparison. The aim of this investigation is an in-depth analysis of the existing methods and the proposition of a framework for modeling road transport noise emissions in LCI in accordance to the requirement profile postulated in part 1.

Materials and methods This paper analyzes three methods for inclusion of traffic noise in LCA (Danish LCA guide method, Swiss EPA method, and Swiss FEDRO method) in detail. The additional basis for the analysis are the Swiss road traffic emission model "SonRoad," traffic volume measurements at 444 sites in the Swiss road network, vehicle-type-specific noise measurements in free floating traffic situations in Germany, and noise emission measurements from different tires.

Results The Danish LCA guide method includes a major flaw that cannot be corrected within the methodological concept. It applies a dose–response function valid for average noise levels of a traffic situation to maximum noise levels of single vehicles. The Swiss FEDRO method is based on an inappropriate assumption since it bases distinctions of specific vehicles on data that do not allow for such a distinction. Noise emissions cannot be distinguished by the make and type of a vehicle since other factors, especially the tires, are dominant for noise emissions. Several problems are also identified in the Swiss EPA method, but they are not of a fundamental nature. Thus, we are able to base a new framework for vehicle and context-sensitive inclusion of road traffic noise emissions in LCI on the Swiss EPA method. We show how specific vehicle classes can be distinguished, how the influence of different tires can be dealt with, and what temporal and spatial aspects of traffic need to be distinguished.

Discussion While the Danish LCA guide method and the Swiss FEDRO method are not suitable for our purpose, the Swiss EPA method can be used as a basis to better meet the requirement profile identified in Part 1 of this paper. The proposed method for consistent, context-sensitive modeling of noise emissions from road transports in LCI meets all the requirements except that it is restricted to road transport.

Responsible editor: Ralph Rosenbaum

This paper consists of two parts. Part 1 analyzes the background and state of the art of traffic noise assessment in LCA. Part 2 undertakes a detailed analysis of existing methods and proposes a framework for a context-sensitive method for the consistent inclusion of relevant human health effects of generic road transportation noise.

Electronic supplementary material The online version of this article (doi:10.1007/s11367-009-0117-1) contains supplementary material, which is available to authorized users.

H.-J. Althaus (✉)
Technology and Society Laboratory,
Swiss Federal Laboratories for Materials Testing and Research (Empa),
Ueberlandstrasse 129,
8600 Duebendorf, Switzerland
e-mail: hans-joerg.althaus@empa.ch

H.-J. Althaus · P. de Haan · R. W. Scholz
Natural and Social Science Interface,
Institute for Environmental Decisions, ETH Zurich,
Universitaetstr. 22,
8092 Zurich, Switzerland

Conclusions We show limitations of the existing methods and approaches for improving them. Our proposed model allows for a more specific consideration of the various vehicles and contexts in terms of space and time and thus in terms of speed and traffic volume. This can be used on one hand for a consistent, context sensitive assessment of different vehicles in different traffic situations. On the other hand, it also allows for an inclusion of noise in LCA of transports on which only very little is known. This new LCI model meets five of the six requirements postulated in Part 1.
Recommendations and perspectives In a next step, additional noise emissions due to additional traffic needs to be calculated based on the proposed framework and national or regional traffic models. Furthermore, the consideration of noise from different traffic modes should be addressed. The approach presented needs to be extended in order to make it also applicable for rail and air traffic noise, and the methods need to be implemented in LCI databases to make them easily available to practitioners. Furthermore, suitable impact assessment methods need to be identified or developed. They could base on the proposals made in the Swiss EPA and in the Swiss FEDRO methods.

Keywords Additional noise emission · LCA · LCI · Traffic noise · Transport

1 Background, aim, and scope

Effects of traffic noise have been widely assessed and compared to other effects of traffic in many studies (e.g., Clark et al. 2006; Griefahn et al. 2006; Hyder et al. 2006; Lam et al. 2009; Ohrstrom and Skanberg 2004a, b; Öhrström et al. 2006; Peris and Pescador 2004; Persson Waye 2004; Raschke 2004; Sandrock et al. 2008; Skånberg and Öhrström 2006; Spreng 2004; Stassen et al. 2008; Wirth 2004); furthermore, some methodologies for including traffic noise in LCA have been proposed (Doka 2003; Guinée et al. 2001; Heijungs et al. 1992; Müller-Wenk 2002, 2004; Nielsen and Laursen 2005; Potting and Hauschild 2003). Part 1 of this paper (Althaus et al. 2009) aims at analyzing the requirements for such methods and at identifying the compliance of existing methods with these requirements. In this second part, we analyze the existing methods in detail and, based on the most promising existing methods[1], we propose a context-sensitive framework for the consistent life cycle inventory (LCI) modeling of road transportation noise, which is in accordance with the requirement profile proposed in Part 1. Therefore, we need data and models for traffic volumes and noise emissions from cars and traffic situations. We are using measurements of the average traffic volume at 444 sites in the Swiss road network (ASTRA and BfS 2006b), the Swiss SonRoad model for noise emissions (Heutschi 2004b), and TÜV measurements for noise emissions of specific vehicle (Steven 2005) and tire types (Reithmaier and Salzinger 2003).

1.1 SonRoad

The influences of assumptions and simplifications used in the methods proposed by Nielsen and Laursen (2005) (hereafter called "Danish LCA guide" method), Müller-Wenk (2002, 2004) (hereafter referred to as the "Swiss EPA" method), and Doka (2003) (hereafter called the "Swiss FEDRO" method) are analyzed in detail using the traffic noise calculation model SonRoad[2] (Heutschi 2004a,b).

SonRoad (Heutschi 2004b) gives Eqs. 1 and 2 for the calculation of the maximum noise levels for rolling noise and propulsion noise from a vehicle passing at constant speed on a flat road paved with mastic asphalt, measured at 7.5 m from the lane. The coefficients for lorries and passenger cars are given in Table 1. Equation 3 is used for the addition of Eqs. 1 and 2, resulting in the maximal sound level of one vehicle passing measured at 7.5 m from the lane. The average sound level (L_{eq}) in distance d [m] from the lane of the passage of n vehicles per hour with a maximum sound level $L\max$ is calculated using Eq. 4. Equation 5 adds the equivalent sound levels of different types of vehicles and results in the total equivalent sound level. Equation 6 finally is used to calculate the corresponding maximal sound level 10 m from the lane.

$$L\max_{roll,7.5m,A} = a + 35 \times \log(v) + D_{roll} \ldots [\mathrm{dB(A)}] \qquad (1)$$

$$L\max_{prop,7.5m,A} = b + 10 \times \log\left(1 + (v/c)^{3.5}\right) + D_{prop} \ldots [\mathrm{dB(A)}] \qquad (2)$$

$$L\max_{7.5\mathrm{m,A}} = 10 \times \log\left(10^{\left(L\max_{\mathrm{roll,7.5m,A}} \times 10^{-1}\right)} + 10^{\left(L\max_{\mathrm{prop,7.5m,A}} \times 10^{-1}\right)}\right) \ldots [\mathrm{dB(A)}] \qquad (3)$$

$$L_{\mathrm{eq}_{n,A}} = L\max_{7.5m,A} - 10 \times \log(v) - 10 \times \log(d) - 7.5 + 10 \times \log(n) \ldots [\mathrm{dB(A)}] \qquad (4)$$

[1] A short description of the existing methods is given in Part 1. Extracts of the original publications of the methods are reproduced in Annex 1 to the Electronic supplementary material (ESM 2).

[2] Extracts of the original publication of the method are reproduced in Annex 1 to the ESM 2.

Table 1 Coefficients to be used with Eqs. 1 and 2 (Heutschi 2004b)

Vehicle type	*a*	*b*	*c*
Lorries and heavy motorcycles (type 2)	18.5	76.9	56
Passenger cars and vans (type 1)	9.5	62.7	44

$$L_{eq_{total}} = 10 \times \log \left(10^{\left(L_{eq_1} \times 10^{-1}\right)} + 10^{\left(L_{eq_2} \times 10^{-1}\right)} + \ldots + 10^{\left(L_{eq_x} \times 10^{-1}\right)}\right) \ldots [dB(A)] \quad (5)$$

$$L\max_{10m,A} = L\max_{7.5m,A} + 20 \times \log(7.5/10) \ldots [\mathrm{dB(A)}] \quad (6)$$

where:

$L\max_{roll,7.5\,m,A}$	maximum A-weighted sound level from rolling at 7.5 m distance in [dB(A)]
$L\max_{prop,7.5\,m,A}$	maximum A-weighted soundlevel from propulsion at 7.5 m distance in [dB(A)]
a, b, c	coefficients, depending on vehicle type (Table 1)
$L\max_{7.5\,m,A}$	maximum A-weighted sound level at 7.5 m distance in [dB(A)]
D_{roll}	correction for road surface-tire combination [dB(A)]
D_{prop}	correction for engine load [dB(A)]
v	vehicle speed [km/h]
d	distance of receiver to traffic lane centre [m]
n	number of vehicles per hour [/h]
1—*x*	index for different vehicle types

1.2 Vehicle specific sound emissions

In order to test the results from the Swiss FEDRO method we used vehicle type specific sound levels measured by TÜV in real traffic situations[3] (Steven 2005). These measurements show that noise limit reductions for type approval, which came into force between 1978 and 2002 in Germany, did not lower the noise level of passenger cars in free flowing traffic situations (Steven 2005). The study also provides fit curves for the noise emissions of different vehicle types. Equation 7 is valid for passenger cars and vans, while equation 8 is to be used for different lorries. Table 2 gives the coefficients to be used with these equations.

Steven found no significant differences for passenger cars with different rated power, power/mass ratio and engine capacity in free flowing traffic situations. However, he found a difference between passenger cars (PC) with different engine technologies and between light delivery vans (LDV) below and above 2,000 kg gross vehicle mass. (Steven 2005) gives Eq. 7 with coefficients from Table 2 for petrol- and diesel-fueled PC (built after 1995) and LDV below 2 t and for diesel LDV between 2 and 3.5 t.[4] For diesel vehicles, Steven differentiates engines with premixed compressed ignition (PCI) and direct injection (DI). Since the data for LDVs with PCI and DI diesel engines are very close, we combine them by averaging.[5] Passenger cars with the two types of diesel engines differ significantly in their noise emission and thus should not be combined.

Table 2 Coefficients to be used with Eq. 7 (passenger cars and vans) and 8 (lorries) (Steven 2005)

Vehicle type		*a*	*b*
Passenger car	$PC_{petrol>1995}$	13.450	19.541
Passenger car	$PC_{dieselPCI>1995}$	10.029	31.788
Passenger car	$PC_{diesel\ di>1995}$	10.682	32.168
Van	$LDV_{petrol\leq 2t}$	11.313	27.782
Van	$LDV_{diesel\ PCI\leq 2t}$	12.021	25.812
Van	$LDV_{diesel\ di\leq 2t}$	12.116	25.051
Van	$LDV_{diesel\ PCI\leq 2t}$	11.723	28.097
Van	$LDV_{diesel\ di>2t}$	11.873	27.803
Van	$LDV_{diesel\leq 2t}$	12.0685	25.4315
Van	$LDV_{diesel>2t}$	11.798	27.950
Lorry	$HCV_{\leq 3axles,Pn<100kW}$	0.2109	66.131
Lorry	$HCV_{\leq 3axles,100kW\leq Pn<150kW}$	0.2158	67.087
Lorry	$HCV_{\leq 3axles,150kW\leq Pn<250kW}$	0.2141	69.049
Lorry	$HCV_{\leq 3axles,Pn\geq 250kW}$	0.1923	70.852
Lorry	$HCV_{>3axles,Pn\geq 250kW}$	0.1858	72.750

TÜV (Steven 2005) reports significant differences in noise emissions between heavy commercial vehicles with up to three axles and with more than three axles. It also reports differences between vehicles in different ranges of rated power within the category with up to three axles. No such difference was found in the category of vehicles with more than three axles, since the sample of vehicles with a rated power below 250 kW was too small for assessment.

$$L\max_{7.5m,A}(\text{vehicle type}) = a \times \ln(v) + b \ldots [\mathrm{dB(A)}] \quad (7)$$

$$L\max_{7.5m,A}(\text{truck type}) = a \times v + b \ldots [\mathrm{dB(A)}] \quad (8)$$

a, b coefficients, depending on vehicle type (see Table 2)

[3] Extracts of the original publication of the method are reproduced in the Annex 1 to the ESM 2.

[4] No equation for petrol-fueled LDVs above 2 t due to lack of sufficient data.

[5] The difference from the weighted or from the energetic average is negligible.

The *L*max values measured by TÜV (Steven 2005) are compared to those calculated by SonRoad in Figs. 1 and 2 in the Electronic supplementary material (ESM 1).

1.3 Tire-specific sound emissions

Tires play a very relevant role for noise emissions of vehicles, especially at speeds above 50 km/h. Figure 1 shows the average, minimum, and maximum levels for summer and winter tires of different dimensions, measured (at 80 km/h) in a TÜV study of 82 different tires (Reithmaier and Salzinger 2003). Looking at the raw data, we see a weak positive correlation of noisiness with size (stronger for snow tires than for summer tires). Over all sizes, there is no difference in noisiness between winter and summer tires. However, for the smaller sizes, the summer tires are rather louder than the winter tires, while for larger sizes, it is the opposite. Even though the sample in this study (Reithmaier and Salzinger 2003) is relatively small and might not be representative, it can be concluded that the differences in noise levels of specific tires are large and that there is no simple explanation for these differences. Over all tires, the loudest tire is more than 5 dB(A) louder than the most quiet one (at 80 km/h), while within the size classes, this difference is still up to 4.42 dB(A).

2 Analysis of existing methods for inclusion of traffic noise in LCA

2.1 Danish LCA guide method

The "Danish LCA guide" method for traffic noise inclusion in LCA (Nielsen and Laursen 2005) was developed in the context of the Danish LCA guide (Potting and Hauschild 2003), which emphasizes spatial differentiation in LCA. The method is briefly presented in Part 1. It is the only existing method allowing for inter-modal comparison of transports. However, it uses noise nuisance factors derived from a single survey from 1989 in which factors are independent of the source of noise. This contradicts the generally accepted fact that noise levels causing equivalent effects can differ by up to 10 dB(A) for two different traffic noise sources. For annoyance, this difference is about 5 dB between road and rail traffic (Miedema and Oudshoorn 2001; Miedema and Vos 1998). Thus, the method overestimates the effect of rail traffic relative to the road traffic effects.

Furthermore, the Danish LCA guide method overestimates the effects of road traffic due to a simplification introduced in the calculation procedure. The equation for calculating nuisance factors from noise levels is developed to be used with an average sound level, i.e., the equivalent sound level. However, the "Danish LCA guide" method applies this formula to the maximum sound level of a single vehicle. This is done since the noise effect in LCA needs to relate to the functional unit, which is the transport and not the traffic situation. However, since the traffic situation, not the single vehicle, is responsible for the average sound level emitted along a road, it is obvious that the error introduced by this simplification depends on the traffic situation. We use the Swiss traffic noise calculation model SonRoad (Heutschi 2004a,b) to estimate this error. Table 3 shows a comparison of maximum and equivalent sound levels for different traffic situations and the corresponding noise nuisance factors. The calculation of the values is documented in the ESM 1. The simplification in the "Danish LCA guide" method is justified for traffic situations in which maximum and equivalent sound levels are equal. The method thus overestimates the effect of traffic noise as long as e.g. less than 1,852 trucks per hour are driving at 50 km/h on a certain road. Thus, by using the maximum sound levels of single vehicles, the Danish LCA guide method overestimates the effect of the vehicle's noise by a factor of between 2 and 10 as long as the total number of trucks is in a reasonable range, i.e. below 1,000 vehicles per hour.

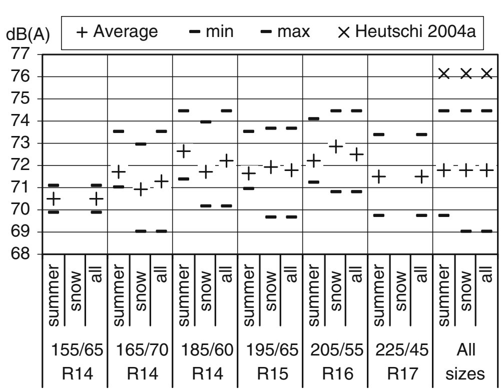

Fig. 1 Average rolling noise levels of 82 different tires at 80 km/h (Reithmaier and Salzinger 2003) and rolling noise at 80 km/h calculated with Eq. 1 (Heutschi 2004b)

2.2 Swiss EPA method

Müller-Wenk (2002, 2004) developed a method for the inclusion of road traffic noise in LCA for the Swiss EPA (Swiss Federal Office for the Environment), which is briefly described in Part 1. The method is very well suited for an assessment of generic road traffic, but it needs to be amended in order to allow for an assessment of specific vehicles and traffic situations.

Table 3 Maximal sound levels (*L*max) of a single truck passing and 24-h average sound level (L_{eq}) of traffic situations with *n* trucks per hour at the speeds (*v*) used in the Danish LCA guide method (Nielsen and Laursen 2005)

Speed [km/h]	Number of vehicles [/h]	Lmax (10m) [dB(A)]	L_{eq} (10m) [dB(A)]	Back-ground noise level (K) [dB(A)]	Noise nuisance Factor [*L*max (10m)]	Noise nuisance factor [L_{eq} (10m)]
50	10	79.1	57.1	50	0.775	0.086
50	100	79.1	67.1	50	0.775	0.234
50	1,000	79.1	77.1	50	0.775	0.635
50	1,582	79.1	79.1	50	0.775	0.775
85	10	85.7	61.4	41	3.687	0.325
85	100	85.7	71.4	41	3.687	0.883
85	1,000	85.7	81.4	41	3.687	2.400
85	2,689	85.7	85.7	41	3.687	3.687
105	10	88.7	63.5	36	8.239	0.662
105	100	88.7	73.5	36	8.239	1.800
105	1,000	88.7	83.5	36	8.239	4.892
105	3,321	88.7	88.7	36	8.239	8.239

The Danish LCA guide method uses maximal levels to calculate noise nuisance factors (NNF). However, NNF should be calculated using equivalent sound levels L_{eq}

2.2.1 Expansion for intra-modal comparison

The Swiss EPA method distinguishes only between types 1 and 2 vehicles. Type 1 vehicles are passenger cars and utility vans up to 3.5 t gross vehicle mass, and type 2 vehicles are all heavy vehicles (>3.5 t gross vehicle mass) and heavy motorcycles. However, there are significant differences in noise emissions between different vehicles within these classes. Thus, distinctions need to be made if an LCA compares different vehicles for the same transport (e.g. lorry, 3.5–7 t versus lorry, 40 t). In line with this, the Swiss FEDRO method (Doka 2003) proposes a way of introducing a differentiation for passenger cars (see Section 2.3), and we propose a way for introducing this differentiation for various types of passenger cars, vans and trucks in Section 3.

2.2.2 Distinction of motorcycles and heavy vehicles for determination of additional traffic

The Swiss EPA method assumes additional heavy vehicle traffic to be proportional to the existing type 2 (i.e. heavy vehicles and heavy motorcycles) traffic in every place on the road network. Because, in Switzerland, heavy motorcycle traffic is high on roads with very low overall total traffic, especially during the weekends,[6] this assumption results in high additional lorry traffic on these roads, which in reality exhibit very low proportions of heavy vehicles. This artifact leads to an overestimation of results by around 25%, which is easily avoided by assuming additional heavy vehicle traffic to be proportional to existing heavy vehicle traffic (Figs. 2a and b, based on calculations[7] and measurements of average traffic volume at 444 sites in the Swiss road network (ASTRA and BfS 2006b)).

2.2.3 Discrimination of workdays and weekends

The Swiss EPA method does not discriminate between weekends and workdays even though heavy vehicle traffic in Switzerland (and possibly in other countries) is considerably lower on Sundays than during the week. Thus, a discrimination of workday and Sunday traffic should be made if significant differences in the effects of additional traffic are expected. Figure 2a and c shows that the additional noise from additional heavy vehicles and from additional type 2 vehicles (heavy vehicles and heavy motorcycles) on Sundays is about twice as high as on the average day (including weekends). This is due to the traffic volume of heavy vehicles being much lower on weekends than on weekdays. The wide distribution of additional noise data that can be seen in Fig. 2c for additional traffic being proportional to type 2 traffic is due to the fact that, for small roads, type 2 traffic volume can be higher on weekends due to heavy motorcycle traffic. The overall traffic volume of type 1 vehicles is only slightly lower on weekends than on weekdays. Thus, one might expect not to see a significant difference in additional noise data of type 1 vehicles. However, in fact, the additional noise due to additional type 1 vehicle traffic is about 50% higher on Sundays than on

[6] According to data from (ASTRA and BfS 2006b). It is unclear if this is also true for other European countries.

[7] Calculation of L_{eq} values using Eqs. 1, 2, 3 and 4 with D_{roll}=0 and D_{prop}=0. ΔL_{eq} is calculated as $L_{eq}(n+\Delta n)-L_{eq}(n)$ according to Müller-Wenk 2002.

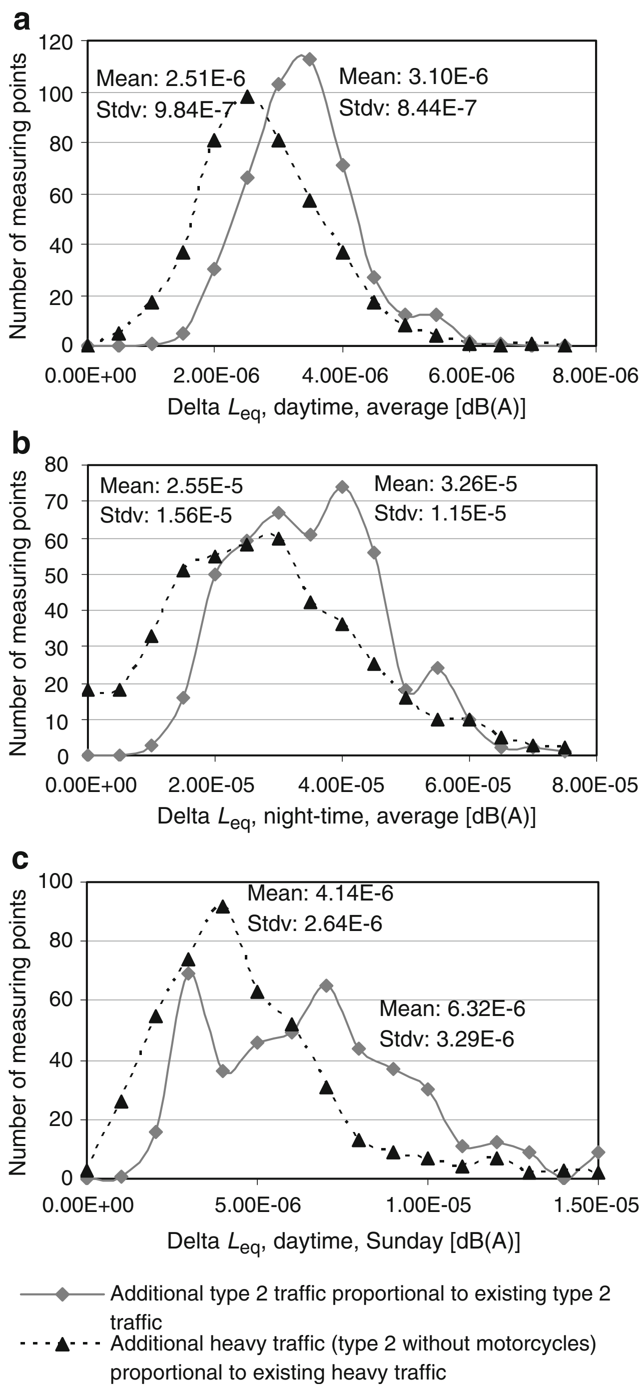

Fig. 2 Distribution of ΔL_{eq} values for one additional heavy vehicle, distributed over the 444 measuring sites in the Swiss road network proportionally to the existing type 2 traffic (including motorcycles) and to the existing heavy vehicle traffic (without motorcycles). Data for **a** the average day, daytime (0600–2200 hours), **b** the average day, nighttime (2200–0600 hours) and **c** Sunday, daytime. Calculations based on a Swiss traffic survey (ASTRA and BfS 2006b)

average days. The main reason for this is the lower overall traffic noise due to reduced noise from type 2 vehicles. Thus, the Swiss EPA method underestimates the effects of weekend traffic, since it overestimates the total traffic noise due to the overestimated share of loud vehicles. Consequently, noise effects on workdays are overestimated. This can be adapted by discriminating between transports on weekdays and weekends.

2.2.4 Discrimination of road classes

Measured traffic volume data (ASTRA and BfS 2006b) was used to test Müller-Wenk's proposition that, with the assumption on proportionality being true, additional traffic noise is independent of existing traffic volume and can thus be averaged for all types of roads without weighting. Figure 3a and b shows the additional noise due to one additional vehicle distributed over the 444 measured sites

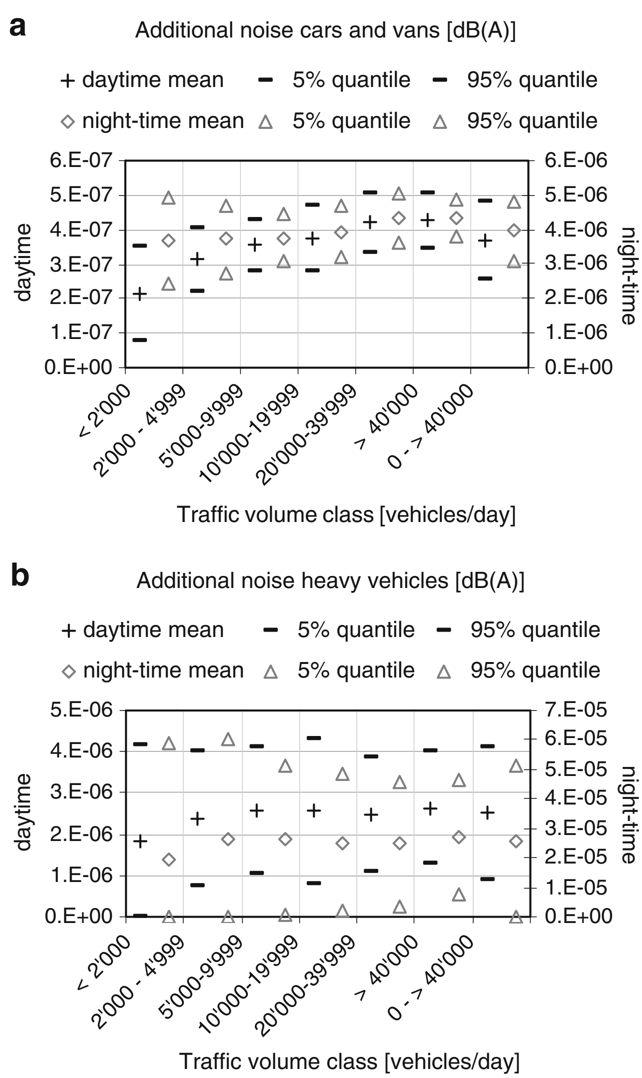

Fig. 3 ΔL_{eq} values for one additional vehicle, distributed over the 444 measuring sites in the Swiss road network proportionally to the existing traffic. Data for the average day and for: **a** type 1 vehicles, **b** type 2 vehicles without motorcycles. Measuring sites are classified according to the total traffic volume on an average day. Calculations based on a Swiss traffic survey (ASTRA and BfS 2006b)

proportionally to the existing traffic volume of this vehicle type versus the total existing daily traffic volume in six classes, derived from 444 measured sites in Switzerland (ASTRA and BfS 2006b). A statistically significant difference in additional noise levels is found for daytime traffic of cars and vans on roads with very low and very high overall traffic volume. Thus, Müller-Wenk's proposition on independence is not supported by these data. The weak positive correlation of additional noise with existing traffic volume observed for day- and nighttime and for all types of vehicles actually suggests that additional noise due to additional traffic, which is proportional to the existing traffic, might not be independent of traffic volume. However, the wide range over which the additional noise levels are scattered suggests that they are influenced by other variables, e.g. the type of road, which determines the speed. Thus, Müller-Wenk's assumption might be reasonable for the assessment of the effect of generic road traffic, but for a context-sensitive assessment, a classification of roads according to traffic volume seems worthwhile.

2.2.5 Proportionality of additional traffic

Müller-Wenk's assumption that additional traffic is distributed on the road network proportionally to the existing traffic does not hold true. In Switzerland, traffic volumes increase more on roads with large existing traffic volumes (ASTRA and BfS 2001, 2006a). Traffic volume on Swiss national highways increased by about 45%, traffic volume on country roads increased by about 10% between 1990 and 2005, while traffic volume in towns and cities rose less than 4% in the same period (ASTRA 2008). Traffic on national highways increased steadily, while the changes of the traffic volume on the other roads were not constant. However, in every single year, traffic volume increase on national highways was higher than it was on other roads. Over that same period, the total length of national highways increased by only 18% while that of the other roads remained constant (BfS 2008). Thus, since the additional noise from additional traffic depends on road type (speed) and traffic volume and since additional traffic is not independent of the type of road, we propose to discriminate between road classes and aggregate the classes to a generic class in proportion to overall traffic. The uncertainty introduced in the Swiss EPA method by the unweighted averaging of additional noise levels over all traffic situations can thus be reduced.

2.2.6 Assumptions on speed

The Swiss EPA method calculates noise levels using assumed vehicle speeds, which are, with the exception of heavy vehicles on motorways, lower than the values given in SonRoad (Heutschi 2004b). SonRoad reports a 5–25 km/h higher speed for passenger cars than for heavy vehicles if the signaled speed is 80 km/h or above and 3–4 km/h higher speeds for all vehicles during the day than during the night. Since lower speed leads to less traffic noise, speed assumptions in the Swiss EPA method overestimate the additional noise due to additional traffic.

2.2.7 Extension for inter-modal comparison

From a practitioner's point of view, the method also needs to be extended to rail and air traffic noise, since these three modes of traffic are often compared with each other. Whether noise from ships can be neglected in this context needs to be further assessed. Transoceanic cargo ships could cause health effects among people living near harbors, and noise from barges on canals might cause human health effects among the population living along the canal. However, since traffic volume on canals is rather small compared to road traffic, the magnitude of these effects is probably much smaller than for road, rail or air traffic. However, noise from ship transports might have significant effects on the marine ecosystem.

2.3 Swiss FEDRO method

Doka (2003) proposed ecological scarcity factors for the inclusion of road traffic noise in the Swiss Eco-Scarcity method (Brand et al. 1998) based on the Swiss EPA method, which is briefly described in Part 1. He introduced vehicle specific noise emissions based on type approval measurements for passenger cars. This method thus addresses the problem with the Swiss EPA method described in Section 2.2.1.

2.3.1 Suitability of type approval measurements

By using the average noise level of all type approval measurements and the average noise level of vehicles in a real traffic situation, the Swiss FEDRO method (Doka 2003) assumes that vehicles that are louder in the test approval measurement are also louder in a real traffic situation. However, this is contradicted by measurements of noise levels of passenger cars in free flowing traffic situations in Germany (Steven 2005). Steven concludes that noise limit reductions for type approval, which came into force between 1978 and 2002 in Germany, did not lower the noise level of passenger cars in free flowing traffic situations. The main reason for this might be the measuring conditions for the type approval, which have nothing in common with a real traffic situation. For type approval, the maximum sound level of a vehicle in 10 m distance from the lane is measured while the vehicle accelerates full throttle in second or third gear at 50 km/h.

This full throttle situation directly increases propulsion noise, while the rolling noise component is influenced only indirectly, via the change in the vehicle speed due to 10 m full throttle acceleration. Thus, type approval values are dominated by propulsion noise. Since, in free flowing traffic at 50 km/h, the rolling noise contributes more than propulsion noise to the overall noise of a passenger car [see Fig. 2 in Part 1 (Althaus et al. 2009)], it is obvious that test approval measurements do not correspond to noise emissions in free flowing traffic.

3 Proposal of a new framework for modeling road transport noise emissions in LCI

3.1 Basis of new framework

Based on the requirement profile postulated in Part 1 and on the analysis of the methods in Section 2, we propose to use the Swiss EPA method as a basis for a new framework, which allows for an adequate consideration of generic and specific road transports. Our framework adopts the concept of calculating additional noise emissions due to additional vehicles. However, instead of calculating only generic values for daytime and nighttime transports by passenger cars and trucks, we propose to calculate specific values for various specific vehicles and situations based on the issues discussed in Section 2.2. The shortcomings of the Swiss EPA method concerning the distinction of heavy vehicles and heavy motorcycles for the calculation of the additional traffic (Section 2.2.2) and concerning the vehicle speeds on different roads for the calculation of sound levels (Section 2.2.6) should thereby be rectified.

3.2 Distinction of specific vehicles

Additional emissions should be calculated using a vehicle-specific emission model based on SonRoad (Heutschi 2004b) and TÜV measurements (Steven 2005). We are using SonRoad as the basis because it is the official Swiss emission model and since it allows for a specific consideration of the road surface and inclination as well as of the tires of the vehicles. The discrimination of different types of passenger cars, vans and different types of heavy vehicles is introduced via vehicle-specific correction factors calculated from the average difference between the SonRoad and the TÜV curves. Equation 9 is used to calculate the absolute correction term to adjust the data from TÜV (Steven 2005) to the data from SonRoad (Heutschi 2004b) with minimal deviation in a given speed range. In Eq. 9, the difference between the $L\max_{7.5,A,SR}$ and $L\max_{7.5,A,St}$ is calculated where SR is the SonRoad and St the Steven related value, v_1 and v_2 denote two speeds v and $\mathrm{Abs_{Corr}}$ a constant for correction. It can be easily resolved to Eqs. 10 and 11:

$$\int_{v_1}^{v_2} \left(L\max_{7.5m,A,SR} - L\max_{7.5m,A,St} + Abs_{Corr} \right) dv = 0 \ldots [\mathrm{dB(A)}] \tag{9}$$

$$\int_{v_1}^{v_2} L\max_{7.5m,A,SR}\, dv - \int_{v_1}^{v_2} L\max_{7.5m,A,St}\, dv + \int_{v_1}^{v_2} Abs_{Corr}\, dv = 0 \ldots [\mathrm{dB(A)}] \tag{10}$$

$$Abs_{Corr} = \left(\int_{v_1}^{v_2} L\max_{7.5m,A,St}\, dv - \int_{v_1}^{v_2} L\max_{7.5m,A,SR}\, dv \right) \times (v_2 - v_1)^{-1} \ldots [\mathrm{dB(A)}] \tag{11}$$

with $L\max_{7.5,A,St}$ as the noise level calculated according to Eqs. 7 or 8 and $L\max_{7.5,A,SR}$ as the noise level calculated according to Eqs. 1, 2, and 3. Since the weighted sum of all specific vehicles needs to be the original function from SonRoad, a relative correction is calculated by Eq. 12.

$$\mathrm{Rel}_{\mathrm{Corr,type}X} = \mathrm{Abs}_{\mathrm{Corr,type}X} - \sum_{\mathrm{type}X=1}^{n} \left(\mathrm{share}_{\mathrm{type}X} \times \mathrm{Abs}_{\mathrm{Corr,type}X} \right) \ldots [\mathrm{dB(A)}] \tag{12}$$

The proportions of the specific types of heavy vehicles are those found by TÜV (Steven 2005). In addition, the ratio of passenger cars (92.15%) to vans (7.85%) is taken from TÜV (Steven 2005). This ratio is very close to that observed in Swiss traffic monitoring, where 91.16% passenger cars and 8.84% vans were counted (ASTRA and BfS 2006b). At the time of the measurements used for the SonRoad model, almost no diesel passenger cars were used in Switzerland. Consequently, a proportion of 100% petrol-fueled passenger cars is used in the calculation, even though the proportion of diesel cars is much higher in the TÜV measurements (Steven 2005). The values for the correction terms and the proportions are given in Table 4. The integration is carried out in the speed range between 30 and 120 km/h for passenger cars and vans and between 30 and 100 km/h for trucks, since these are reasonable ranges for normal operations and since, for speeds below 30 km/h, the regression models from TÜV (Steven 2005) and SonRoad (Heutschi 2004b) are not valid. For a range of 30–140 km/h, the resulting relative corrections for passenger cars and vans would differ by about 10%. If a speed range of 30–120 km/h were chosen for heavy vehicles, the relative correction values would differ less than 10% for three of the specific lorries. For the two lorries with less than three axles and more than 150 kW rated power, the relative correction would change +45% (150–250 kW) and −26% (>250 kW), respectively. Thus, the choice of the speed range for the calculation of the correction term is relevant in these cases. The values from Table 4 can be used in Eq. 13 for the calculation of the noise levels of the different vehicles.

$$L\max_{7.5\mathrm{m,A,type}X} = 10 \times \log\left(10^{\left(L\max_{\mathrm{roll},7.5\mathrm{m,A}} \times 10^{-1}\right)} + 10^{\left(L\max_{\mathrm{prop},7.5\mathrm{m,A}} \times 10^{-1}\right)}\right) + \mathrm{Rel}_{\mathrm{Corr,type}X} \ldots [\mathrm{dB(A)}] \quad (13)$$

with $L\max_{7.5,A}$ and $L\max_{\mathrm{prop},7.5,A}$ calculated using Eqs. 1 and 2.

To calculate the additional noise from an additional vehicle of type X, the equivalent noise levels from types 1 and 2 vehicles in a certain traffic situation (with the corresponding numbers of types 1 and 2 vehicles) are calculated using Eqs. 4 and the results from Eqs. 1, 2 and 3. Then, the equivalent noise level from the additional vehicle is calculated using Eqs. 4 with $n = 1$ (since it is one additional vehicle) and $L\max_{7.5,\mathrm{A,type}X}$. The additional noise is the difference between the energetic sum of all three equivalent noise levels and the energetic sum of the two equivalent levels in the basis situation (see Eq. 14).

$$\Delta L_{\mathrm{eq}} = 10 \times \log\left(10^{\left(L_{\mathrm{eq}_{\mathrm{n,d,type1}}} \times 10^{-1}\right)} + 10^{\left(L_{\mathrm{eq}_{\mathrm{n,d,type2}}} \times 10^{-1}\right)} + 10^{\left(L_{\mathrm{eq}_{\mathrm{n,d,type}X}} \times 10^{-1}\right)}\right) - 10 \times \log\left(10^{\left(L_{\mathrm{eq}_{\mathrm{n,d,type1}}} \times 10^{-1}\right)} + 10^{\left(L_{\mathrm{eq}_{\mathrm{n,d,type2}}} \times 10^{-1}\right)}\right) \ldots [\mathrm{dB(A)}] \quad (14)$$

Table 4 Proposed absolute and relative correction values for introducing a better differentiation of specific vehicle classes in the SonRoad model

	Share	$\mathrm{Abs}_{\mathrm{Corr}}$	$\mathrm{Rel}_{\mathrm{Corr}}$
Passenger cars and vans (type 1)	Percent	v = 30–120	km/h
Passenger car $\mathrm{PC}_{\mathrm{petrol}>1995}$	85.7	0.750	−0.080
Passenger car $\mathrm{PC}_{\mathrm{diesel\ PCI}>1995}$	2.68	2.709	1.879
Passenger car $\mathrm{PC}_{\mathrm{diesel\ DI}>1995}$	3.77	1.614	0.784
Van $\mathrm{LDV}_{\mathrm{petrol}\leq 2\mathrm{t}}$	0.75	−0.090	−0.920
Van $\mathrm{LDV}_{\mathrm{diesel}\leq 2\mathrm{t}}$	0.89	0.770	−0.060
Van $\mathrm{LDV}_{\mathrm{diesel}>2\mathrm{t}}$	6.20	2.139	1.309
All type 1 vehicles (weighted)	100	0.830	
Heavy vehicles (type 2)	%	v=30–100	km/h
Lorry $\mathrm{HCV}_{\leq 3\mathrm{axles,Pn}<100\mathrm{kW}}$	4.93	−4.605	−3.661
Lorry $\mathrm{HCV}_{\leq 3\mathrm{axles,100kW}\leq \mathrm{Pn}<150\mathrm{kW}}$	19.96	−3.331	−2.387
Lorry $\mathrm{HCV}_{\leq 3\mathrm{axles,150kW}\leq \mathrm{Pn}<250\mathrm{kW}}$	15.06	−1.479	−0.535
Lorry $\mathrm{HCV}_{\leq 3\mathrm{axles,Pn}\geq 250\mathrm{kW}}$	4.34	−1.093	−0.149
Lorry $\mathrm{HCV}_{>3\mathrm{axles,Pn}\geq 250\mathrm{kW}}$	55.71	0.391	1.335
All type 2 vehicles (weighted)	100	−0.944	

Own calculations, based on SonRoad (Heutschi 2004b) and TÜV measurements (Steven 2005). Proportions of heavy vehicles and LDVs according to TÜV measurements (Steven 2005). Overall proportions of passenger cars according to TÜV measurements (Steven 2005). Ratio of petrol/diesel passenger cars is assumed to be 100% petrol for the time of the SonRoad measurements in Switzerland

3.3 Distinction of specific tires

The average of all tires measured in the TÜV study (Reithmaier and Salzinger 2003) is 4.31 dB(A) lower than what can be calculated for rolling noise at 80 km/h using Eq. 1. This may be for various reasons: other tire technology, other road surface, other tire operation (pressure, load, wear and temperature), unrepresentative sample in the TÜV study (Reithmaier and Salzinger 2003) and uncertainties derived from splitting the real traffic situation measurements into rolling and propulsion noise components in SonRoad (Heutschi 2004b). Whatever the reason might be, the big difference implies that, in order to compare vehicles with different tires, it is necessary to calculate the tire corrections to be used in SonRoad relative to the average of the various emission levels of the tires to be compared. If, for example, we want to compare a vehicle with every 165/70 R14 tire reported by (Reithmaier and Salzinger 2003), we calculate the average sound emission of all tires of this size [71.29 dB(A)] and deduct the sound emission level of each individual tire to get the rolling noise correction for this specific tire. This rolling noise correction can then be used in SonRoad in the same way as rolling noise corrections for different road surfaces (in Eq. 1). Thus, a car running at 50 km/h with the loudest 165/70 R14 tires reported in Reithmaier and Salzinger (2003) would be almost twice as loud [2.8 dB(A) louder] as the same car with the most quiet tires of this size[8].

3.4 Consideration of context

We have shown in Sections 2.2.3, 2.2.4 and 2.2.5 that a consideration of road classes (traffic volume and speed) and a distinction between weekdays and weekends influences the additional noise from additional traffic significantly, even if the additional traffic considered is proportional to the existing traffic. The fact that additional traffic is more likely to occur on specific road classes (national highways) further highlights the consequence that additional noise

[8] Calculated using Eqs. 1, 2 and 3 with $D_{\mathrm{roll,min}} = -2.28$ (average noise level of 165/70 R14 tires−noise level of least noisy 165/70 R14 tire) and $D_{\mathrm{roll,max}} = 2.20$ (average noise level of 165/70 R14 tires−noise level of noisiest 165/70 R14 tire).

levels per vehicle-kilometre are needed for weekdays and weekends for different classes of roads. How the roads should be classified could be assessed by clustering the additional noise emissions from additional traffic distributed over the countries (or regions) road network. However, this only would take into account the emission side of the problem. Since LCA is not only interested in emissions but also impacts, a discrimination of road classes should be made based on effects, also taking into account the population densities along the roads. The traffic model used for this clustering can also be used for the determination of the weights of the specific combinations of workday or weekend with road classes, which need to be used to calculate generic additional emission values per additional vehicle-kilometre.

4 Discussion, conclusion and recommendations

Some serious shortcomings were identified in the Danish LCA guide method and in the Swiss FEDRO method for the inclusion of traffic noise. The Swiss EPA method exhibits no problems of a fundamental nature and thus, if the shortcomings of this method are overcome, provides a good basis for a new, context-sensitive framework. The proposed new framework allows for a more specific consideration of the various vehicles and contexts in terms of space and time and thus in terms of speed and traffic volume. Therefore, the resulting additional noise levels due to additional traffic are more precise and distinctive. This new method meets five of the six requirements postulated in Part 1 (Althaus et al. 2009). Since we use measurements of real traffic situations for the distinction between various vehicle categories, the findings might not be representative for new vehicles. Thus, careful interpretation is necessary if the results are to be used to support purchase decisions.

Additional noise levels for additional transports will have to be calculated based on the proposed framework and national or regional traffic models. The results will need to be implemented in LCI databases in order to make them easily available for the practitioners. In future research, we also intend to address the fourth requirement identified in Part 1 (Althaus et al. 2009): a method that is consistent with the presented approach needs to be developed for rail and air traffic noise. Therefore, a major challenge will be the consideration of noise from mixed sources (Lam et al. 2009; Miedema 2004).

Acknowledgements We thank Gabor Doka, Ruedi Müller-Wenk and the anonymous reviewers for their valuable comments and inputs to the paper, Kurt Heutschi and Kurt Eggenschwiler from the Empa acoustic laboratory for the fruitful discussions and the Swiss Federal Office for the Environment for financial support.

References

Althaus H-J, De Haan P, Scholz RW (2009) A methodological framework for consistent context-sensitive integration of noise effects from road transports in LCA. Part 1: Requirement profile and state-of-science. Int J Life Cycle Assess, doi:10.1007/s11367-009-0116-2

ASTRA, BfS (2001) Schweizerische Strassenverkehrszählung 2000, Bundesamt für Strassen (ASTRA), Neuchatel

ASTRA, BfS (2006a) Schweizerische Strasenverkehrszählung 2005, Bundesamt für Strassen (ASTRA), Neuchatel

ASTRA, BfS (2006b) Schweizerische Strasenverkehrszählung 2005–Datenbank. Bundesamt für Statistik (BfS), Neuchatel

ASTRA (2008) Etwicklungsindizes des Schweizerischen Strassenverkehrs. Fortschreibung 1995–2007. Bundesamt für Strassen (ASTRA), Bern

BfS (2008) Streckennetz nach Verkehrsträgern. Bundesamt für Statistik (BfS), Neuchatel

Brand G, Scheidegger A, Schwank O, Braunschweig A (1998) Bewertung in Ökobilanzen mit der Methode der ökologischen Knappheit-Ökofaktoren 1997. SRU 297, Swiss Agency for Environment, Forest and Landscape (SAEFL), Bern

Clark C, Martin R, van Kempen E, Alfred T, Head J, Davies HW, Haines MM, Barrio IL, Matheson M, Stansfeld SA (2006) Exposure-effect relations between aircraft and road traffic noise exposure at school and reading comprehension—The RANCH project. Am J Epidemiol 163:27–37

Doka G (2003) Ergänzung der Gewichtungsmethode für Ökobilanzen Umweltbelastungspunkte' 97 zu Mobilitäts-UBP' 97. Doka Ökobilanzen, Zurich

Griefahn B, Marks A, Robens S (2006) Noise emitted from road, rail and air traffic and their effects on sleep. J Sound Vib 295:129–140

Guinée JB, Gorrée M, Heijungs R, Huppes G, Kleijn R, de Koning A, van Oers L, Wegener Sleesewijk A, Suh S, Udo de Haes HA, de Brujin H, van Duin R, Huijbregts MAJ, Lindeijer EW, Roorda AAH, van der Ven BL, Weidema BP (2001) Life cycle assessment: an operational guide to the ISO Standards. Final Report, May 2001, Ministry of Housing, Spatial Planning and Environment (VROM) and Centrum voor Milieukunde (CML), Rijksuniversiteit, Den Haag and Leiden

Heijungs R, Guinée JB, Huppes G, Lankreijer RM, Udo de Haes HA, Wegener Sleeswijk A, Ansems AMM, Eggels PG, van Duin R, de Goede HP (1992) Environmental life cycle assessment of products, guide and background. Centre for Milieukunde (CML), Leiden

Heutschi K (2004a) SonRoad: New Swiss Road Traffic Noise Model. Acta Acustica united with Acustica 90:548–554

Heutschi K (2004b) SonRoad—Berechnungsmodell für Strassenlärm. Environmental Series No. 366, Swiss Agency for Environment, Forest and Landscape (SAEFL), Bern

Hyder AA, Ghaffar AA, Sugerman DE, Masood TI, Ali L (2006) Health and road transport in Pakistan. Public Health 120:132–141

Lam K-C, Chan P-K, Chan T-C, Au W-H, Hui W-C (2009) Annoyance response to mixed transportation noise in Hong Kong. Appl Acoust 70:1–10

Miedema HME (2004) Relationship between exposure to multiple noise sources and noise annoyance. J Acoust Soc Am 116:949–957

Miedema HME, Vos H (1998) Exposure response functions for transportation noise. J Acoust Soc Am 104:3432–3445

Miedema HME, Oudshoorn CGM (2001) Annoyance from transportation noise: relationships with exposure metrics DNL and DENL and their confidence intervals. Environ Health Perspect 109:409–416

Müller-Wenk R (2002) Attribution to road traffic of the impact of noise on health. Environmental Series No. 339, Swiss Agency for Environment, Forest and Landscape (SAEFL), Bern

Müller-Wenk R (2004) A method to include in lca road traffic noise and its health effects. Int J Life Cycle Assess 9:76–85

Nielsen PH, Laursen JE (2005) Integration of external noise nuisance from road and rail transportation in lifecycle assessment. Danish Environmental Protection Agency, Copenhagen

Ohrstrom E, Skanberg A (2004a) Sleep disturbances from road traffic and ventilation noise-laboratory and field experiments. J Sound Vib 271:279–296

Ohrstrom E, Skanberg A (2004b) Longitudinal surveys on effects of road traffic noise: substudy on sleep assessed by wrist actigraphs and sleep logs. J Sound Vib 272:1097–1109

Öhrström E, Skånberg A, Svensson H, Gidlöf-Gunnarsson A (2006) Effects of road traffic noise and the benefit of access to quietness. J Sound Vib 295:40–59

Peris SJ, Pescador M (2004) Effects of traffic noise on paserine populations in Mediterranean wooded pastures. Appl Acoust 65:357–366

Persson Waye K (2004) Effects of low frequency noise on sleep. Noise Health 6:87–91

Potting J, Hauschild M (eds) (2003) Danisch LCA Guide (final draft). Danish Environmental Protection Agency

Raschke F (2004) Arousals and aircraft noise—environmental disorders of sleep and health in terms of sleep medicine. Noise Health 6:15–26

Reithmaier W, Salzinger T (2003) Survey on motor vehicle tyres and related aspects. TÜV Automotive, Munich

Sandrock S, Griefahn B, Kaczmarek T, Hafke H, Preis A, Gjestland T (2008) Experimental studies on annoyance caused by noises from trams and buses. J Sound Vib 313:908–919

Skånberg A, Öhrström E (2006) Sleep disturbances from road traffic noise: a comparison between laboratory and field settings. J Sound Vib 290:3–16

Spreng M (2004) Noise induced nocturnal cortisol secretion and tolerable overhead flights. Noise Health 6:35–47

Stassen KR, Collier P, Torfs R (2008) Environmental burden of disease due to transportation noise in Flanders (Belgium). Transp Res Part D Transp Environ13:355–358

Steven H (2005) Ermittlung der Geräuschemission von Kfz im Straßenverkehr. TÜV Nord, Würselen

Wirth K (2004) Lärmstudie 2000 Die Belästigungssituation im Umfeld des Flughafens Zürich. PhD Thesis, Universität Zürich, Zürich