

Traffic noise in LCA

Part 1: state-of-science and requirement profile for consistent context-sensitive integration of traffic noise in LCA

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Abstract

Background, aim, and scope According to some recent studies, noise from road transport is estimated to cause human health effects of the same order of magnitude as the sum of all other emissions from the transport life cycle. Thus, ISO 14'040 implies that traffic noise effects should be considered in life cycle assessment (LCA) studies where transports might play an important role. So far, five methods for the inclusion of noise in LCA have been proposed. However, at present, none of them is implemented in any of the major life cycle inventory (LCI) databases and commonly used in LCA studies. The goal of the present paper is to define a requirement profile for a method to include traffic noise in LCA and to assess the compliance of the five existing methods with this profile. It

concludes by identifying necessary cornerstones for a model for noise effects of generic road transports that meets all requirements.

Materials and methods Requirements for a methodological framework for inclusion of traffic noise effects in LCA are derived from an analysis of how transports are included in 66 case studies published in *International Journal of Life Cycle Assessment* in 2006 and 2007, in the sustainability reports of ten Swiss companies, as well as on the basis of theoretical considerations. Then, the general compliance of the five existing methods for inclusion of noise in LCA with the postulated requirement profile is assessed.

Results Six general requirements for a methodological framework for inclusion of traffic noise effects in LCA were identified. A method needs to be applicable for (1) both generic and specific transports, (2) different modes of transport, (3) different vehicles within one mode of transport, (4) transports in different geographic contexts, (5) different temporal contexts, and (6) last but not least, the method needs to be compatible with the ISO standards on LCA. One of the reviewed methods is not specific for transports at all and two are only applicable for specific transports. The other two allow generic and specific road transports to be assessed. The methods either deal with road traffic noise only or they compare noise from different sources, ignoring the fact that not only physical sound levels but also the source of sound determines the effect. Three methods only differentiate between vehicle classes (lorries and passenger cars) while one method differentiates between specific vehicles of the same class. Four of the methods consider the geographic context and three of them differentiate between day- and nighttime traffic.

Discussion None of the existing methods for traffic noise integration in LCA complies with the proposed requirement profile. They either lack the genericness for a wide

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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.

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application or they lack the specificity needed for differentiations in LCA studies. There is no method available that allows for appropriate inter- or intramodal comparison of traffic noise effects. Thus, the benefit of the existing methods is limited. They can, in the better cases, only demonstrate the relative importance of road or rail traffic noise effects compared to the nonnoise-related effects of transportation.

Conclusions Currently, none of the major LCI databases includes traffic noise indicators. Thus, noise effects are usually not considered in LCA studies. We introduce a requirement profile for methods that allow the inclusion of noise in LCI. Due to the estimated significance of noise in transport LCA, this inclusion will change the overall results of many LCA studies. None of the existing methods fully complies with the requirement profile. Two of the methods can be modified and extended for inclusion in generic LCI databases. A third model allows for intermodal comparison. From an LCA perspective, all methods include weaknesses and need to be amended in order to make them widely usable.

Recommendations and perspectives In part 2 of this paper, an in-depth analysis of the promising methods is provided, improvement potential is evaluated, and a new context-sensitive framework for the consistent LCI modeling of noise emissions from road transportation is presented. Appropriate methods for modeling rail and air traffic noise will have to be developed in the future in order to arrive at a methodological framework fully compliant with the requirement profile. Furthermore, future research is needed to identify appropriate methods for impact assessment.

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

1 Background, aim, and scope

The health significance of noise pollution includes various effects: noise-induced hearing impairment; interference with speech communication; disturbance of rest and sleep; psychophysiological, mental health, and performance effects; effects on residential behavior and annoyance; and interference with intended activities (Berglund et al. 1999). Sound pressure levels of 55 and 65 dB(A) are generally regarded as disturbing to sleep and daytime activities, respectively (Berglund et al. 1999). At the end of the 1990s, about 40% of the population of the European Union was exposed to road traffic noise with an equivalent daytime sound pressure level exceeding 55 dB(A), and 20% were exposed to levels exceeding 65 dB(A). At night, more than 30% were exposed to equivalent sound pressure levels exceeding 55 dB(A). When noise from all transportation modes is considered, more than half of all

European Union citizens are estimated to live in zones that do not ensure acoustical comfort to residents (Berglund et al. 1999).

Effects of traffic noise on humans and wildlife have been widely assessed (e.g., Clark et al. 2006; Griefahn et al. 2006; Hyder et al. 2006; Jaeger et al. 2005; Lam et al. 2008; Lengagne 2008; 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). From these and other studies, it is known that effects from environmental noise typically depend on the average sound level over a period of time, usually referred to as equivalent sound level (Leq) and on the context of the sound. This context includes the source of the sound, the time and place of the emission, and individual factors for the exposed persons. Since the source is an important factor for the potential effect, noise from different sources (residential noise, industrial noise, traffic noise, etc.) is usually treated separately. Within traffic noise, usually road, rail and air traffic are differentiated. Many top-down studies show that traffic noise effects on humans significantly contribute to the overall effects of transport services (e.g., Banfi et al. 2000; Beuthe et al. 2002; OCDE 1997; Schreyer et al. 2004). Therefore, the ISO standards for life cycle assessment (LCA; ISO 14'040 2006; ISO 14'044, 2006) imply that human health effects of noise should be considered in LCA studies where transports might play an important role. Since this is often the case (see *ESM*, Sections 1 and 2, and Jørgensen et al. 1996), a bottom-up approach for quantifying the effects of a specific transport is needed. Some bottom-up assessments of external cost and human health effects of traffic noise have been conducted (Bickel and Schmid 2002a, b; Hofstetter and Müller-Wenk 2005; Lafleche and Sacchetto 1997; Lu and Morrell 2006; Martuzzi and Mudu 2006; Meijer et al. 2006; Mudu et al. 2003; Müller-Wenk 2002, 2004; Müller-Wenk and Hofstetter 2003; Schmid et al. 2003; Schreyer et al. 2004; Sommer et al. 2004) and some methodologies to include 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). The results of all of these studies and methods which allow this comparison confirm the relevance of traffic noise effects on overall human health effects. Figure 1 exemplifies this using the method of Müller-Wenk (2002, 2004). The present paper aims at analyzing these methods from a practitioner and practical application perspective. Part 2 of the paper (Althaus et al. 2009) analyzes the most promising methods, focusing on the accuracy of models and the data behind them, and proposes new models and data sources for improving the life cycle inventory (LCI) modeling.

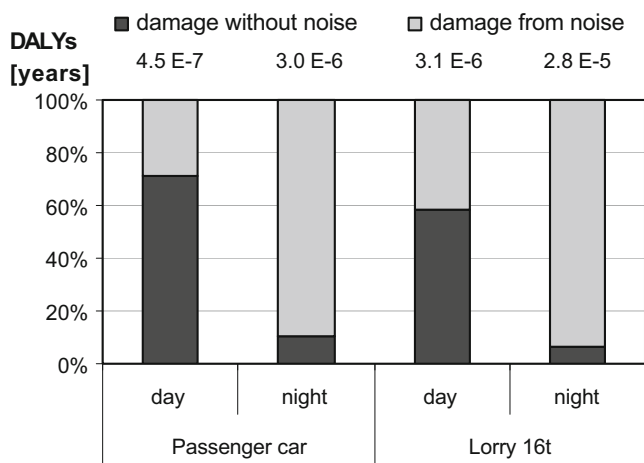


Fig. 1 Contribution of noise damage to Human Health impact of 1 vkm of a passenger car and of a 16-t lorry. Absolute impacts without noise are the same for day and night and based on the ecoinvent 99 (H/A; Goedkoop and Spriensma 2000) implementation in ecoinvent v1.3 (www.ecoinvent.org; Frischknecht et al. (2004); Frischknecht et al. (2005)). Noise damage is based on (Müller-Wenk 2002, 2004)

2 Materials and methods

The strengths and weaknesses of a given method depend on the scope of the LCA (e.g., a detailed model might be prerequisite for intercomparing different cars, but might hinder an application if, e.g., for a generic situation, the required data are not available). Therefore, an analysis of all 66 case studies (CS) published in *International Journal of Life Cycle Assessment* in the years 2006 and 2007 and of the environmental reports of ten Swiss companies (details are given in the *ESM*, Sections 1 and 2) was carried out. Even though LCA studies are also published in other journals than the *International Journal of Life Cycle Assessment*, the sample can be considered representative for the purposes of the present analysis. From this analysis, coupled with theoretical considerations on LCA and traffic noise, a requirement profile for methods to include traffic noise in LCA is proposed. We then assess the compliance of the five methods for the inclusion of (traffic) noise in LCA published so far (Doka 2003; Guinée 2001; Heijungs et al. 1992; Müller-Wenk 2002, 2004; Nielsen and Laursen 2005; Potting and Hauschild 2003) with this requirement profile.

3 Requirements for traffic noise methods in LCA

3.1 Analysis of transports in case studies

Roughly two thirds of the CS include transports in the foreground system. Only one of them (Meijer et al. 2006)

assesses noise effects of transport. In over half of the CS including foreground transports, the authors considered transport contributions to the overall results of the study relevant. For more details, see Table 1. All CS including transports in the foreground system seem to cover at least road transport, even though many are not explicit about what transports are included. Explicitly or implicitly covered are ship transports in 13, rail transports in five, and air transports in four of the CS. More than half of the CS that include transports use generic data from LCI databases (mainly the ecoinvent database (www.ecoinvent.org), BUWAL 250 (Habersatter and Fecker 1996), and ETH-ESU 1996 (Frischknecht et al. 1996)). The reference flow of the transports in those CS is ton kilometers. In order to use these datasets, explicit information on the transport system, the vehicle type, the transport distance, and weight of the transported goods is needed. Assumptions concerning the fuel type, fuel consumption, emission standard, and load factor of the vehicle are made in the dataset itself. The road transports are explicitly modeled in seven of the CS, taking into account information on fuel consumption, emission standards, load capacity, etc. Kilometers (or miles) are used as reference flow in three of these CS, and two studies relate to the fuel consumed (in liters or cubic meter). The reference flow chosen to include transports is unclear for the remaining CS that include transports. One CS adopts cumulative data from another study and ten CS give no information whatsoever on how transports are included, despite the fact that transports are of relevance concerning the overall results of the study in three of them (Table 2). Most of the CS make no explicit statements on how much is known about the specific vehicle type and the route the transport takes. It nevertheless seems reasonable to assume that in most of the cases, some information would be readily available because the transport is accomplished by the company responsible for the product or by a company only one step down the supply chain. Detailed information on the CS can be found in the *ESM* in Chapter 1.

Most of the LCA practitioners use generic transport datasets with a reference flow of ton kilometers (or person-kilometers) for road, rail, ship, and air transports. However, in some CS, additional information on, e.g., the fuel consumption, the emission standard, or the utilization factor of the vehicle is used for road traffic. On the other hand, for rail, ship, and air transport, usually only some geographical information on origin and destination seems to be available, but no specific vehicle characteristics. This implies that transport data need to be compatible for different means and modes of transport and that different degrees of genericness would make sense from a practitioner's point of view.

Table 1 Inclusion and relevance of transports in 66 case studies published in *International Journal of Life Cycle Assessment* in 2006 and 2007

All case studies	Transportation relevant	Transportation negligible	Relevance unknown or n.a.	Total
With transport in foreground	23	21	0	44
With no transport in foreground	1	6	5	12
Unclear if transport in foreground	1	0	0	1
With transport not an issue	0	0	9	9
Total	25	27	14	66

Transport in foreground system means that transports are explicitly modeled while no transport in foreground system means that transports are not explicitly modeled but might be included in background data used in the case study. Transport is not an issue in case studies with scopes that exclude transports

3.2 Analysis of transports in environmental reports

Ten companies were chosen to analyze how transport is assessed in the environmental reports. Two of the companies do not report on environmental issues at all. Another company reports only on energy demand in production, water use, and waste management but not on transports related to its activities. Four out of the remaining seven companies report transport issues as rather relevant. In two companies, transports are of medium relevance, while in only one company that provides telephone and internet services transports are considered not important. All the reports give information on types and emission standards of the vehicles. One company reports only fuel consumption. Another one reports the fuel consumption and two specific emissions (PM₁₀ and NO_x). The other companies report indicators based on life cycle inventories (ecological scarcity points, CO₂ equivalents, carbon footprint). Two of them explicitly use ecoinvent v1.x data while the others are not specific on the data source. In one case, the practitioners using the ecoinvent data needed to adapt them to account for environmental improvements achieved by changes in the fleet, since the ecoinvent v1.x database does not differentiate among various emission standards (Euro 1–5) and provides no data for liquefied petroleum gas or biofuel (biogas, biodiesel, bioethanol) fueled vehicles, and hybrid cars. How the company made this adaptation is not documented. Details can be found in the [ESM](#) in Section 2.

3.3 Theoretical considerations on requirements for transport data

Compliance with the ISO standards (ISO 14'040 2006; ISO 14'044 2006) is an important quality sign for LCA studies, LCI databases, and LCIA methods and should therefore be aimed at. The standards prescribe four phases in an LCA study: goal and scope definition, inventory analysis, impact assessment, and interpretation. These phases relate to each other but are separate. In the LCI phase, physical in- and outputs are compiled; the life cycle impact assessment (LCIA) phase is aimed at evaluating the significance of potential environmental impacts using the LCI results.

Consequently, LCI results need to carry sufficient information to assess the impacts according to the scope definition. Thus, if the LCIA should assess total annoyance or total human health effects due to the exposure to a noise emission, the minimum information needed in LCI data is the sound level, the time of the day (day vs. night), and the source of the sound (road, rail, or air traffic) (Schuemer et al. 2003). Sound is usually measured in decibels, a logarithmic unit for the sound pressure. The contributions of different frequency ranges to the overall level of a sound are usually weighted to account for the individual hearing thresholds for the frequencies. This is notated by adding the weighting index in brackets to the unit (“dB(A)”). Sound levels at a certain location are a composite of individual sound sources, e.g., single car engines, and therefore fluctuate over time. Ambient sound levels are usually integrated over time and then called

Table 2 Use of data and relevance of transports in 44 case studies including transports in foreground, published in *International Journal of Life Cycle Assessment* in 2006 and 2007

Case studies with transport in foreground	Transportation relevant	Transportation negligible	Relevance unknown or n.a.	Total
Generic data	16	11	0	27
Specific data	4	3	0	7
Unknown	3	7	0	10
Total	23	21	0	44

“equivalent sound levels”. The time over which the sound is integrated is given as an index. L_{eq} is usually calculated for a whole day (24 h) or for daytime (16 h) and nighttime (8 h) separately. The latter two indexes are then called L_{eqD} and L_{eqN} . These two indicators are sometimes combined to a “day–night level”, L_{eqDN} , which is the addition of the two after 10 dB(A) is added to the night hours to account for larger effects of noise during nighttime. Even though weighted sound levels are not strictly physical flows, they are still potential LCI parameters according to the standard (ISO 14'040 2006), which foresees not only physical data but also data for “other environmental aspects” to be included in the inventory.

According to the standard, the “functional unit [of an LCA] defines what is being studied. All subsequent analyses are then relative to that functional unit, as all inputs and outputs in the LCI and consequently the LCIA profile are related to the functional unit.” (ISO 14'040 2006). The functional unit of generic datasets for transports with reference flows person kilometer, ton kilometer, or vehicle kilometers, relates to a vehicle in a generic (often average) traffic situation (Spielmann and Scholz 2005). This implies that the inventory flows in the LCI data need to relate to the generic situation and that these generic LCI flows need to allow for a sensible impact assessment. Figure 2 shows that the sound emissions from single vehicles strongly depend on the vehicle's speed. It has to be noted that, due to the logarithmic character of the decibel unit, an increase of 20 dB corresponds to a sound energy which is 100 times higher. Thus, within a reasonable range

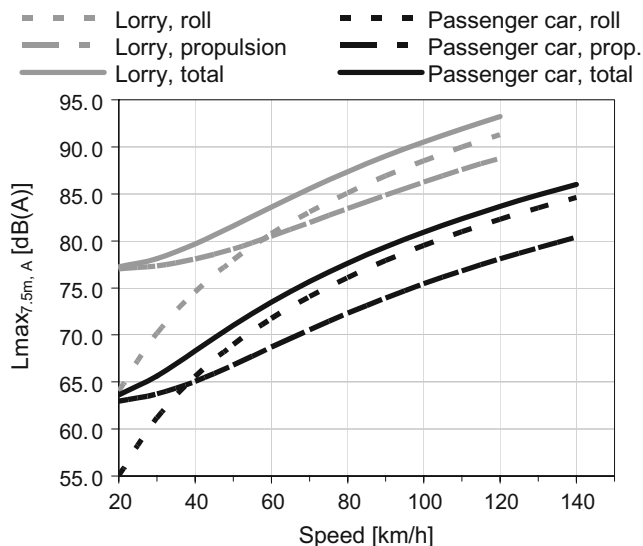


Fig. 2 Maximal sound levels of single vehicles passing 7.5 m from measurement position as a function of vehicle speed. Calculation according to Heutschi (2004b) without rolling and propulsion corrections ($D_{roll} = 0$ and $D_{prop} = 0$), thus corresponding to a flat road, paved with mastic asphalt. Rolling noise, propulsion noise, and total

of vehicle speed, the sound emission energy varies in a range of two orders of magnitude. But the maximum sound level from a single vehicle is still not sufficient for assessing the impact of traffic noise, since noise effects are usually related to time-averaged equivalent sound levels, i.e., L_{eq} . Figure 3 shows that the equivalent sound level caused by road traffic varies within two orders of magnitude with the number of vehicles. Also, the curve is not linear but much steeper for low numbers of vehicles than it is for high numbers. Thus, the change of the noise level due to a marginal change in the number of vehicles depends on the absolute number of vehicles. This implies that temporal and spatial aspects need to be considered in the functional unit of (generic) transport LCI data since vehicle speed and traffic volumes are highly dependent on time and place. The traffic volume for the average day at the 444 measurement sites in Switzerland given in reports of Swiss national agencies (ASTRA, BfS 2006a, b) lies between less than 1,000 and almost 120,000 vehicles per day. Maximum and minimum hourly traffic for the average day at one site vary by up to a factor of 197. Figure 4 illustrates average daily traffic data (in a logarithmic representation since differences are enormous) for different classes of roads.

3.4 Requirement profile for noise inclusion methods for LCA

Based on Sections 3.1, 3.2, and 3.3, we postulate the following requirements. In order to ensure wide applicability in LCA studies, a method needs to allow for:

1. Consideration of generic and specific transports in LCA
2. Separate treatment of different modes of transport
3. Separate treatment of different vehicles within one mode of transport
4. Accounting for transports in different geographic contexts
5. Accounting for different temporal contexts of transports
6. Compliance with ISO 14'040/44

The first requirement ensures that transport data are included in LCA studies as accurately as possible, i.e., that all relevant information which is available can be used. Often, information is not sufficient for specific modeling of transports in LCA studies. Other studies and environmental reports of companies need a specific consideration of transports and comparison of transport alternatives (e.g., between road and rail or Euro 3 and Euro 4 truck). This is reflected by requirements 2 and 3. Requirements 4 and 5 ensure that spatial and temporal aspects which are very important for noise emissions and effects but are usually neglected in LCA are heeded. Noise emissions of transports are highly dependent on the geographical context, mainly

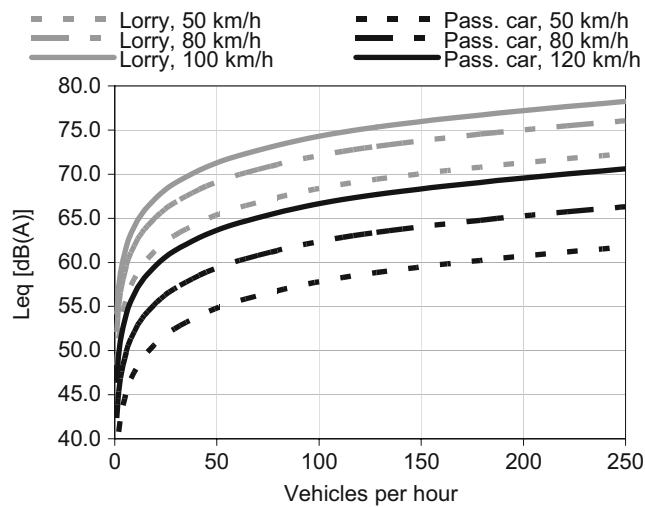


Fig. 3 Equivalent sound levels of vehicles passing 7.5 m from measurement position as a function of number of vehicles per hour. Calculation according to Heutschi (2004b) without rolling and propulsion corrections ($D_{roll} = 0$ and $D_{prop} = 0$), thus corresponding to a flat road, paved with mastic asphalt

traffic speed and volume. Especially traffic volume depends on the time of the day and also on the day of the week. Noise propagation and damage caused by traffic noise depend on the geographical context (mainly shielding effects and local population density). Noise effects also depend on the intended activity of the exposed persons, which again depends on the time of the day. Together with requirement 6, these requirements implicitly determine that

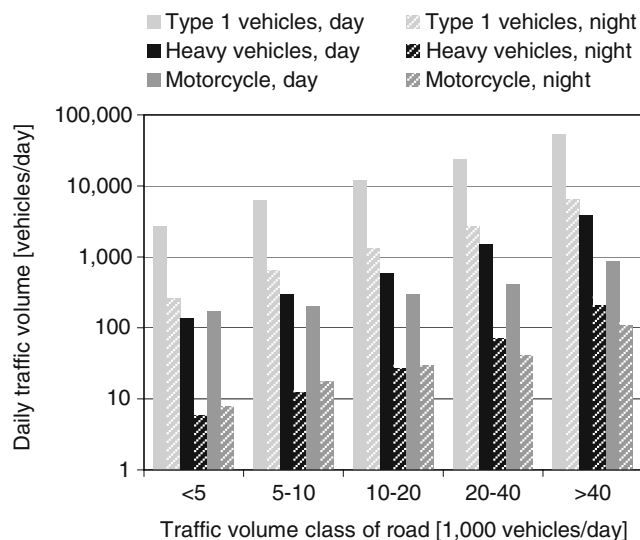


Fig. 4 Average traffic volume per day (logarithmic representation!), measured at 444 sites on roads in different traffic volume classes in Switzerland. The number of vehicles varies by more than one order of magnitude for different classes of roads and for day- and nighttime. Raw data from ASTRA, BfS (2006a). Type 1 vehicles refers to passenger cars and vans up to 3.5 t

a method for the inclusion of traffic noise in LCA needs to be generic and thus suitable for inclusion in generic LCI databases. However, at the same time, the method needs to respect the temporal and spatial context of the transport and its contribution to the sound level and the effects.

4 Existing methodological approaches for the inclusion of traffic noise in LCA

Five different methodologies for the inclusion of (traffic) noise in LCA have been proposed so far. Table 3 shows how these methods comply with the requirement profile postulated above. The methods are very shortly described in Sections 4.1 to 4.5. For a more detailed description, please refer to the original publications or to the extracts from the original publications reproduced in Annex 1 to the ESM.

4.1 CML guide for LCA

The CML guide for LCA (Guinée et al. 2001; Heijungs et al. 1992) proposes an unweighted aggregation of sound, in energy density per time units (Pascal-squared second or (joule per cubic meter)-squared second). This indicator is not limited to traffic noise but could be used for stationary sources of sound as well. This measure of sound energy has been criticized as being useless, since it depends on the measurement point (Lafleche and Sacchetto 1997). It should thus be integrated over the volume of the portion of space affected by noise to be suitable for LCA studies, which is claimed to be impossible due to lack of data (Lafleche and Sacchetto 1997). Another difficulty with this index is that it adds sound energy disregarding temporal and spatial aspects as well as all the situational and individual factors determining the perception and effect of the sound. Thus, even though the CML guide indicator could be calculated for any situation, it is rated not suitable for all the different comparisons in Table 3, since differences in the indicator values would not reflect differences in human health effects.

4.2 Ecobilan method

Lafleche and Sacchetto presented the first specific “methodological attempt” (Lafleche and Sacchetto 1997, p. 111) at traffic noise assessment in LCA. Their starting points are calculated or measured noise levels along traffic infrastructure and noise thresholds for day- and nighttime. From that, they calculate the surface of the area affected by noise above threshold and the perpendicular distance from the road encompassing disturbed people. This threshold distance is multiplied by the local population density and

Table 3 Compliance of existing methods for inclusion of (traffic) noise in LCA with the postulated requirements (Section 2.1.3)

Method	CML guide ^a	Ecobilan method ^b	Danish LCA guide ^d	Swiss EPA method ^f	Swiss FEDRO method ^g
Short characterization of the method	Unspecific physical addition of energy	Site specific threshold exceedance from road traffic	Context ignoring nuisance from site specific road and rail traffic	Generic additional DALYs from generic additional road traffic	Generic additional environmental scarcity points from specific additional road traffic
Suitable for generic and specific transports in LCA	No	No	No	Yes	Yes
Comparison of different modes of transports	No	No	Yes ^c	No	No
Comparison of different vehicles within one mode of transport	No	Rough ^c	Rough ^c	Rough ^c	Yes ^h
Suitable for comparison of transports in different geographic contexts	No	Yes	Yes	Yes	Yes
Suitable for comparison of transports in different temporal contexts	No	Yes	No	Yes	Yes
Complies to ISO 14'040	Yes	No	No	Yes	Yes

An in-depth discussion of the methods is presented in Althaus et al. (2009). For details, see part 2 of this paper (Althaus et al. 2009)

^a Guinée et al. (2001), Heijungs et al. (1992)

^b Lafleche and Sacchetto (1997)

^c Differentiates lorry and passenger car only

^d Nielsen and Laursen (2005)

^e Road and rail differentiated in an inappropriate way

^f Müller-Wenk (2002, 2004)

^g Doka (2003)

^h Differentiates specific vehicles. However, differentiation is based on inappropriate data for characterizations

the result is integrated over the total length of the trip. Thus, the number of instantaneously disturbed persons along the infrastructure of the trip is derived. Finally, the effect is allocated to single vehicles and functional units. This procedure allows for an assessment of a specific road trip but provides no means for assessing generic transports other than averaging all specific road trips in a region of interest. Also, the number of people living in areas above threshold values is a very rough indicator for health effects of noise since effects start occurring below threshold and since they continuously increase with increasing noise level above the threshold.

4.3 Danish LCA guide method

Another method for including specific traffic noise in LCA (Nielsen and Laursen 2005) was proposed as part of the Danish LCA guide (Potting and Hauschild 2003), which emphasizes spatial differentiation in LCA. The method calculates the “noise nuisance impact potential” in person seconds. It is based on a “noise nuisance factor” (NNF_{Lp}),

i.e., the number of persons affected by the peak noise of a single vehicle and the duration of the noise. The NNF_{Lp} represents the inconvenience caused by the noise to humans as a function of the part of the noise that exceeds the background noise. It is a subjective parameter which was determined for traffic noise in interviews. Sound pressure levels are calculated by emission and propagation modeling according to the Nordic prediction method (Nordic Council of Ministers 1996); for exposure modeling, average population densities are applied. The method provides calculation routines for three different sizes of lorries on three different types of road in five different areas and for a train in two different areas. Thus, this method distinguishes different traffic situations and can be applied to freight transports by road and rail. It could easily be expanded to include passenger transport in cars, buses, and trains and the principle could also be applied to air traffic noise, and even though temporal aspects are not taken into account, the possibility of differentiating daytime and nighttime noise is proposed in the outlook (Nielsen and Laursen 2005). Unfortunately, the accessible information does not

allow for a reconstruction of the calculation¹. This method directly calculates noise impacts for a unit process, but does not provide LCI parameters for the noise emission of this unit process and is thus not suitable for inclusion in generic LCI databases. On the other hand, the method is designed to satisfy the need for specific consideration of geographic context. However, it overestimates road traffic effects due to the use of maximal sound levels instead of equivalent sound levels in the calculation of the impact and does not consider the source specificity of impacts when comparing road to rail traffic. For a detailed discussion of the method, see part 2 (Althaus et al. 2009).

4.4 Swiss EPA method

The first method for generic road transports was proposed by Ruedi Müller-Wenk (2002, 2004). Based on the Swiss traffic noise model from 1991 (SAEFL 1991), it calculates marginal noise levels for additional passenger cars and lorries in various real traffic situations in Switzerland. Müller-Wenk presumes that if the available information on a road transport does not indicate the routing but is restricted to the amount of vehicle kilometers driven on a country's road network, the best guess is to assume that the transport is distributed fractionally over the whole road network, in proportion to the preexisting traffic on each of the road segments. Müller-Wenk further suggests that under this assumption, it can be shown that the additional transport increases the noise level in dB, on each of the road segments, by roughly the same amount. As a consequence, the increase of the road noise exposure of the country's whole population, due to the additional transport, can be calculated easily: It is a constant shift of the whole population's preexisting road noise distribution toward a marginally higher level. If dose–effect relationships are available for noise-related health effects, it is then possible to derive the numbers of additional health cases from this constant shift toward marginally higher road noise levels. Thus, generic additional noise levels (ΔL) for 1,000 km additional transports on the Swiss road network are calculated for passenger cars and lorries for day- and nighttime. The additional effects are calculated based on marginally increased data of the actual exposure in the Canton of Zurich extrapolated to the whole of Switzerland. The effects considered are communication and sleep disturbance. Based on a Swiss survey made in 1990 (Oliva 1998), a linear increase in sleep and communication disturbance with increasing sound level and threshold

levels where sound starts to become disturbing was approximated. Thus, the effect analysis results in additional cases of communication and sleep disturbance due to the additional transports. These effects could be used as midpoint results in LCA. However, the Swiss EPA method went one step further by assessing the damage caused by these effects. Therefore, disability weights for communication and sleep disturbance were established and used. Thus, the final result is presented in disability adjusted life years lost (DALYs) and can be directly compared with damage to human health through toxic emissions, calculated, e.g., according to the EcoIndicator 99 (Goedkoop and Spriensma 2000), or through accidents. This method fully complies with the relevant standards (ISO 14'040, 2006; ISO 14'044 2006) and is suitable for inclusion in background LCI databases. Its major drawback is that it only provides data for two generic types of road vehicles and for an average additional journey. Thus, comparisons of different means of transport (e.g., train versus road), of different vehicles of the same type (e.g., lorry A versus lorry B), and of different routes taken (e.g., national highway vs. country road) are not possible. However, the general framework can also be applied to specific vehicles and to specific journeys if the information on vehicle specific emission, local traffic volumes, and on population densities along the roads is known. The adaptation of the method to rail and air traffic noise is possible if for those modes of transport, the assumption on additional traffic being proportional to existing traffic holds true and if additional noise for these modes is also therefore independent of the location of the emission. Due to assumptions and simplifications, especially due to the lack of differentiation of heavy vehicles from motorcycles, the method, however, might overestimate noise effects, especially for heavy vehicles. For a detailed discussion of the method, see part 2 (Althaus et al. 2009).

4.5 Swiss FEDRO method

The Swiss EPA method (Müller-Wenk 2002, 2004) was used as a basis for the method developed for the Swiss Federal Roads Office (FEDRO) (Doka 2003). It proposes ecological scarcity factors for road traffic noise in accordance with the Swiss Eco-Scarcity method (Brand et al. 1998), which calculates burden factors by relating actual flows to the square of critical flows. The Swiss FEDRO method chose the number of highly annoyed people as actual flow and 20% of the Swiss population as critical flow. This critical flow is derived from the immission threshold in Switzerland, which is set to a level where 20% of the population is highly annoyed by the noise. The actual flow is derived from the exposure data from the Swiss EPA method (Müller-Wenk 2002) and from effect curves based on the Swiss survey from 1990 (Oliva 1998). Thus, burden

¹ The background document for this method (Nielsen and Laursen 2005) refers to an Excel tool for the actual application of the method. This file could be retrieved neither from the authors nor from the publisher of the method (Danish EPA).

factors per highly annoyed person for day- and nighttime noise are calculated. The number of highly annoyed persons is calculated based on Müller-Wenk's (2002) method but the emission model was changed to a more recent one (Heutschi 2004a, b). Effect analysis ends at the chosen midpoint of highly annoyed persons. The Swiss FEDRO method also introduced vehicle specific noise emissions, based on type approval noise tests, and showed that noise effects vary by approximately a factor of four for vehicles with type approval values between 69 and 75 dB (A). This method is thus generic in terms of time and place of the emissions and specific in terms of the vehicle and additionally allows for intramodal comparison of vehicles. However, there is even evidence from measurements that vehicles with lower noise values from test approval measurement do not necessarily cause lower sound emissions in real traffic situations (Steven 2005). Thus, type approval test results are not suitable for use in combination with the empiric noise emission calculation procedure proposed in SonRoad (Heutschi 2004b). For a detailed discussion, see part 2 (Althaus et al. 2009).

5 Discussion

A requirement profile for methods to include traffic noise effects in LCA was developed based on a sample of 66 LCA case studies, eight environmental reports, and theoretical considerations. This requirement profile is very difficult to meet since it demands genericness and consideration of spatial and temporal aspects at the same time. Existing methods either lack the genericness for a wide application or lack specificity for the differentiations needed in LCA studies. The Swiss EPA method (Müller-Wenk 2002, 2004) introduces a highly promising way of dealing with this problem for road traffic noise. Based on that, the Swiss FEDRO method (Doka 2003) additionally allows an intramodal comparison beyond that of lorries and passenger cars. Meeting the demand for intermodal comparisons is attempted by the Danish LCA guide method (Nielsen and Laursen 2005) but the method directly calculates noise impacts for a unit process, but does not provide LCI parameters for the noise emission of this unit process and is thus not suitable for inclusion in generic LCI databases.

6 Conclusions and recommendations

A method complying with the requirement profile is needed since an inclusion of traffic noise effects could considerably change the overall results of many LCA studies. However, since none of the existing methods fully complies with the

requirement profile, none of the major LCI databases includes traffic noise indicators. Moreover, noise effects are usually not considered in LCA including transports. Two of the methods proposed so far are in principle suitable for inclusion in generic LCI databases and a third allows for intermodal comparison. However, the methods need to be thoroughly analyzed and weaknesses need to be amended in order to make them widely usable.

An in-depth analysis of the promising methods is made and improvement potential is evaluated in part 2 (Althaus et al. 2009), where also a new framework for context-sensitive inclusion of relevant human health effects from road transportation noise is proposed. Appropriate methods for rail and air traffic noise will have to be developed in the future since noise effects are also relevant in these contexts (e.g., Brons et al. 2003; Clark et al. 2006; Griefahn et al. 2006; Lam et al. 2008; Lu and Morrell 2006; Miedema 2004; Raschke 2004; Sandrock et al. 2008; Schuemer et al. 2003; Wirth 2004). Thus, a methodological framework fully compliant with the requirement profile can be achieved.

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