Estimates of road, rail and airplane noise damages for Life Cycle Assessment

Author

Gabor Doka
Doka Life Cycle Assessments
Zürich

Final Draft Version 2 Zürich, December 2009

Significant Digits

Figures in the inventory tables of this report often feature several digits. This is not to imply that all the digits are really significant or that the data displayed is very precise (it is mostly not). Showing several digits helps to minimise the avoidable accumulation of rounding mistakes along the chain of calculations performed here, and in possible future studies referring to this data. Rounding can introduce significant and entirely avoidable errors in derived data.

The decimal point is indicated like this: 123.45
The three-digit-group separator is indicated like this: 1'000'000 = one million.

Author: Gabor Doka, Doka Life Cycle Assessments, Zurich, do@doka.ch

Picture on title page: Mexico City

1 Introduction

Damages from traffic noise are a relevant part of environmental burdens[1]. However, traffic noise damages are rarely included in environmental life cycle assessments (LCA). None of the major standard impact assessment methods in LCA includes noise damage burdens[2]. The goal of LCA is a synoptic view of environmental damages inflicted by consumer products and services. Any assessment gaps within LCA risk to cause burden-shifting: the mere *transfer* of environmental burdens from heeded damages to the not heeded ones, instead of *prevention* of burdens. Ten years have gone by since first detailed studies for valuation of traffic noise in LCA have appeared, but as yet none of those works have been included in impact assessment methods. One reason for this might be, that LCIA developers deem it unfair to heed road traffic noise, but to ignore rail and airplane noise, and that assessment of traffic noise should be applied to all modes of transport[3].

Any important assessment gaps jeopardize the quality of LCA-based decisions. To avoid such gaps, first multi-modal damage factors for traffic noise are estimated here, based on existing noise damage cost studies.

[1] For example a Dutch study concluded that traffic noise causes human health damages in the order of 28'750 disability-adjusted life years lost per year (DALY/yr) in the Netherlands [De Hollander 1999]. This is significant compared to other damages that are assessed in LCA: 175'000 DALY/yr for particulate mater emission (PM), 1400 DALY/yr for summer smog (Ozone), 240 DALY/yr from polyaromatic hydrocarbon emissions (PAH) (all national sources).

[2] Neither Eco-indicator'99 nor CML'01 do have such factors. Müller-Wenk [1999, 2002] developed factors for road transport in 1999 with the unit DALY per vkm, which would be compatible with the damage units of Eco-indicator'99. Doka [2003] developed similar factors to be used with the Swiss Ecoscarcity method (UBP). For the Dutch EDIP'97 method factors were developed with the unit 'annoyed-persons·seconds/vkm' [Nielsen & Laursen 2000]. Neither of these approaches are included in standard LCIA implementations of LCA databases and are therefore largely not applied in LCA.

[3] The authors of the Swiss ecoscarcity LCIA method have given such rationale to disregard studies compatible with their method, which were on road noise only [ÖBU 2008].

2 Estimation approach

The goal of this report is to make estimates of noise damages compatible with LCA by analyzing existing traffic noise external cost studies. To achieve this, proportionality factors between monetary damages and damages expressed in LCA studies are established. The proportionality factors can then be used to derive first estimates for damages for a variety of transport means.

2.1 Road and rail noise damage costs

Sommer et al. [2008] assesses *total external costs* of Swiss road and rail traffic in 2005. This includes also *noise damage costs* expressed as damages to human health (illness and death due to noise-induced ischemic heart disease and high blood pressure, decrease of life quality) and as decreases in residential property value due to noise, see [Sommer et al. 2004, p.4]. The results are detailed for different transport modes as annual total external cost for, annual noise damage costs and total external costs per vehicle-kilometre. This allows to calculate the noise damage costs alone per vehicle-kilometre listed in Tab. 2.1[4]. For rail transport the vehicle refers to an average train composition, not one wagon alone.

Tab. 2.1 Noise damage costs in Swiss Francs (CHF) per vehicle-kilometre calculated from data in [Sommer et al. 2008].

Vehicle	**Noise damage costs in CHF per vehicle-kilometre** CHF/vkm
Car	0.00980
Motorcycle	0.10544
Moped	0.00787
Public transportation bus	0.1121
Coach	0.1128
Light duty vehicles (LDV) <3.5 Gross-tons [1]	0.0290
Heavy duty vehicles (HDV) >3.5 Gross-tons [2]	0.0953
Articulated lorry (semi-trailer truck) [3]	0.1197
Passenger train	0.3234
Freight train	0.577

1 Ger. 'Lieferwagen'
2 Ger. 'Lastwagen'
3 Ger. 'Sattelschlepper'

[4] Sommer et al. [2008] in Table 2 give only an aggregated sum of *total external* costs of 721 Mio. CHF for motorcycles and mopeds together, but *noise* costs are given separately as 227 resp. 1 Mio. CHF. To calculate the share of noise damages in total external costs for each vehicle type individually, the *total external* costs need to be separated as well. With the separately given figures of 0.28 and 0.93 CHF/vkm *total external* costs for motorcycle and moped, respectively [Sommer et al. 2008, p.5] and an annual sum total of 2280 million vehicle-km for these two types of vehicles together from Spielmann et al. [2007, p.92], one can calculate a consistent solution of 602.8 Mio. CHF *total external* costs for motorcycles alone and 118 Mio. CHF *total external* costs for mopeds alone. This results in 0.10544 and 0.00787 CHF/vkm *noise* costs for motorcycle and moped, respectively.

Sommer et al. [2008] has been criticised by Müller-Wenk to underestimate health cost by using property value losses to assess the health damages from sleep and communication disturbance[5]. For this study the *absolute magnitude* of external noise costs is not relevant, but the *relative* differences between modes of traffic, i.e. road vs. train vs. air vehicles.

The fact that the external costs also include property value loss, can be seen as a conceptual mismatch, as such damages are purely economical in nature and should not be included in *environmental* damage assessments. The authors Sommer et al. however see these losses as a proxy estimator for health damages (sleep and communication disturbance) as pointed out above, and are therefore these costs are admissible also in environmental assessments.

2.2 Airplane noise damage costs

Air traffic noise is not covered in Sommer et al. [2008], but noise damage costs can be obtained from alternate sources. Von Däniken et al. [2002] calculate noise damage costs for the Kloten airport Zurich. Per aircraft movement[6] they calculate noise costs for various scenarios in the range of 510 to 820 Swiss Francs, with a value of 764 Swiss Francs per aircraft movement for the current situation (2000)[7]. This value is used here for average airplane noise[8]. Please note that an aircraft movement is either a landing *or* a take-off. One aircraft journey therefore entails *two* aircraft movements, which are summarised to a so-called landing/take-off cycle (LTO).

Tab. 2.2 Airplane noise damage costs in Swiss Francs (CHF).

		Noise damage costs in CHF per movement(s)
1 average aircraft take-off	CHF/1 movement	764.399
1 average aircraft landing	CHF/1 movement	764.399
1 aircraft landing/take-off-cycle (LTO)	CHF/LTO	1'528.797
1 short-range aircraft LTO	CHF/LTO	576.94
1 long-range aircraft LTO	CHF/LTO	3'266.63

In the Appendix these average figures are attributed to short-and long range flights and the joint-delivered services of passenger and freight transport. The results imply that the noise damage of a

5 See [Müller-Wenk 2003, p.10]: *"... such appraisal methods [monetarisation of noise damages] tend to underweight those forms of damage that only come to light in the long term: the market players concerned are generally unaware of them, and expert knowledge is needed to incorporate them into the methodology. For example, someone who today buys or sells a dwelling with a high level of noise exposure knows much less about the long-term effects of this noise pollution on his health than a specialist physician. Consequently, this aspect surely cannot be adequately reflected in pricing."*

6 Von Däniken et al. [2002] indicates 316'000 aircraft movements ('Flugbewegungen') in Kloten, which presumably are for the year 2000. AFV [2008] indicates 325'622 movements for 2000 and 309'230 movements for 2001 in Kloten, so this matches approximately.

7 Von Däniken et al. [2002] calculates non-recurring property loss damages and recurring external costs. The non-recurring costs were annualised with 5% here to obtain a total annual figure of 242 million Swiss Francs, distributed over 316'000 aircraft movements annually, resulting in 764 Swiss Francs per aircraft movement.

8 A more recent study, [Wittmer et al. 2008], calculates noise damage cost increases between 16.7 and 39.5 million Swiss Francs for increasing the aircraft movements at Kloten from 275'000 in 2008 to a hypothetical 316'250 aircraft movements (+15%). This translates to a range of 405 to 958 Swiss Francs per single aircraft movement, which encloses the range implied in [Von Däniken et al. 2002] and the used mean of 764 Swiss Francs in this study.

short-range flight is 38% of an average flight (576.94 CHF/movement); while the noise damage of a long-range flight is a factor 2.14 of an average flight (3'266.63 CHF/movement).

2.3 Ship noise

Ship noise damage can consist of conceptually similar damages as road, rail and airplane noise damages, i.e. damages to inhabitants near a busy port or waterway. Incidence of such noise exposures seems low, especially in Switzerland where few travelled waterways exist. An older survey from Germany for 1994 maintains that compared to road, rail and airplane noise, the nuisance from ship noise plays no significant role (quoted in BMV 1998)[9].

A rather different issue is marine noise, which is not a damage to humans, but pertains to marine mammals and possibly other biota. There are indications that noise levels in oceans impair the habitat quality and individual health of whales and dolphins and are responsible for a variety of effects like avoidance, hearing loss, communication disturbance and beachings. Apart from freight and passenger ships other marine noise sources contribute to this effect, or might even be dominant, like military submarine detection sonar.

This study extrapolates results from external cost studies looking at health damages and nuisances only in humans. This procedure cannot be extrapolated for damages to a rather different target organism. Results from land-based traffic modes can not be translated into a marine setting. This study can therefore not attempt to estimate noise damages for marine transports. Such studies should however be targeted in the future.

[9] If *country-wide* importance is low, it does not guarantee that in a *product- or service-specific* assessment relevance must be low too. It is imaginable a confined damage leads to significant burdens for a transport service, even if the national relevance is low.

3 Noise damages for ecological scarcity

Doka [2003] derived a noise assessment scheme for individual car models compatible with both the Swiss ecological scarcity method 1997 [Brand et al. 1998] and its update 2006 [ÖBU 2008]. Within the ecological scarcity framework environmental damages are expressed in UBP damage points[10]. For an average car from the EMPA road noise model StL-97, Doka derives an average noise damage of 14.7 UBP per vehicle-kilometre[11]. This value is for a generic share of 7% night driving of cars and 93% during day hours, based on Swiss road traffic statistics. On the other hand, Sommer et al. [2008] specifies noise damage costs for Swiss cars in the order of 0.0098 Swiss Francs per vehicle-kilometre[12]. From this a proportionality of 1499 ecological scarcity points per Swiss Franc noise damage costs can be derived (14.7 UBP / 0.0098 CHF). I will call this entity K_{ES} , the subscript ES standing for ecological scarcity. This value can be used to convert results from noise damage costs in Tab. 2.1 and Tab. 2.2 to LCA-compatible ecological scarcity points.

$$K_{ES} = 1499 \frac{\text{ecological scarcity points UBP}}{\text{Swiss Francs of noise damage costs}}$$

[10] The abbreviation 'UBP' derives from the German 'Umwelt-Belastungs-Punkte' (environmental burden units), the common unit in the Swiss ecological scarcity method.

[11] An average car has a noise level of 71.02 dB at 50km/h. In Doka's model this results in a noise type approval value of 74.16 dB. Such a vehicle has a noise damage of 14.7 UBP/vkm (cf. Figure 2.14 in Doka 2003).

[12] Total annual noise damage costs from cars for Switzerland in 2005 are 501 million Swiss Francs, total annual external costs from cars (including air pollution etc.) are given as 4599 million Swiss Francs, so for cars 10.9% of external costs are noise damage costs. Sommer at al. [2008, p.6] indicates 0.09 Swiss Francs total external costs *per vehicle-kilometre*; and 10.9% of that are noise damage costs, resulting in 0.0098 Swiss Francs per vehicle-kilometre for cars.

Tab. 3.1 Noise damage factors for the environmental scarcity method for road and rail vehicles per vehicle-kilometre.

Vehicle	**Noise damage in environmental scarcity UBP per vehicle-kilometre** UBP/vkm
Car	14.70
Motorcycle	158.05
Moped	11.80
Public transportation bus	168.02
Coach	169.14
Light duty vehicles (LDV) <3.5 Gross-tons, Ger. 'Lieferwagen'	43.48
Heavy duty vehicles (HDV) >3.5 Gross-tons, Ger. 'Lastwagen'	142.89
Articulated lorry (semi-trailer truck), Ger. 'Sattelschlepper'	179.48
Passenger train	484.82
Freight train	865.15

Tab. 3.2 Noise damage factors for aircrafts in the environmental scarcity method.

		Noise damage in environmental scarcity UBP for airplanes
1 average aircraft take-off	UBP/1 movement	1'145'857
1 average aircraft landing	UBP/1 movement	1'145'857
1 aircraft landing/take-off-cycle (LTO)	UBP/LTO	2'291'714
1 short-range aircraft LTO	UBP/LTO	864'857
1 long-range aircraft LTO	UBP/LTO	4'896'785

Using loading factors, average occupancy (and for airplanes average distances travelled) these figures can be transformed into noise damages per person-kilometre or per ton-kilometre. Such figures can be found in the Appendix in Tab. A.5.

4 Noise damages for the DALY scale

The Swiss ecological scarcity method is conceptually a somewhat dated LCIA method. Modern LCIA method are using explicit damage valuation to weigh environmental damages relative to each other, which is lacking in the UBP calculations. For damages to human health, the use of so called 'disability-adjusted life years lost' or DALY has become common. DALYs were first introduced with the Eco-indicator'99 method [Goedkoop et al. 2000]. The DALY scale is an aggregate of fatal and non-fatal human health impairments. A fatal disease or health burden is counted with the years of life lost (YOLL), i.e. the difference between the age of the deceased person and the probable life expectancy. For example a male person aged 25 dying of a car accident in Switzerland represents a damage of 50 DALYs, because life expectancy of Swiss males is 75 years. Non-fatal diseases or health burdens (morbidity) are counted with the years lived with disease (YLD) approach. Here, each disease obtains a *severity weighting* as expressed with the so called disability weight (DW) between one and zero, where zero is perfect health and one is death. The disability weight expresses the health impairment a disease causes the sufferer based on how impaired the ability to lead an autonomous life is[13]. E.g. diabetes has a DW of 0.07; a severe depression has a DW of 0.76. Living 20 years with diabetes this causes 1.4 YLD (=20·0.07); suffering 3 months from a severe depression causes 0.19 YLD (=3/12·0.76). To obtain DALYs from fatal and non-fatal human health impairments the values for years of life lost (YOLL) and years lived with disease (YLD) are simply added together.

Also noise damages can be expressed as impairments to human health on the DALY scale. Ruedi Müller-Wenk made a first detailed approach to valuing traffic noise in LCA [Müller-Wenk 1999]. This resulted in damage factors given in DALY per vehicle-km for driving during day, night or a generic mix. In a later study Müller-Wenk showed that the contribution of impairments with low disability weight (communication and sleep disturbance) were more relevant to the total noise damage effect than mortality and morbidity of the more severe health effects from cardio-vascular disease [Müller-Wenk 2002]. While the latter have high disability weights the case numbers due to noise are small, while for the former have low disability weights but are much more widespread, i.e. have large number of cases.

Doka [2003] has calculated noise damages for cars in DALY per vehicle-km[14]. An average car produces 1.811 micro-DALY noise damages per vehicle-kilometer [15][16]. This value is for a generic share of 7% night driving of cars and 93% during day hours, based on Swiss road traffic statistics. Similar to the calculations above this value can be used to derive a relation between noise damage costs and DALYs. The noise damage costs for Swiss cars are 0.0098 Swiss Francs per vehicle-kilometre, as already derived above. From this a proportionality of 184.74 micro-DALY per Swiss Franc noise damage costs can be derived (1.811 micro-DALY / 0.0098 CHF). I will call this entity K_{DALY}. This value can be used to convert noise damage costs from Tab. 2.1 and Tab. 2.2 into estimates of noise DALY for different means of transport.

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[13] This means that disability weights are also depending on the level of care, understanding or support one subject can receive in its respective social environment. E.g. pigment discoloration (vitiligo) on face in less developed countries can have high disability weights near 0.5; in Europe the DW for vitiligo is only 0.02.

[14] The values of [Doka 2003] are used here for consistency with the above UBP calculations. The DALY/vkm figures of [Müller-Wenk 2002] are smaller than those of [Doka 2003]. This is probably due to the use of a different effect curve, i.e. percent affected persons versus traffic noise level.

[15] An average car has a noise level of 71.02 dB at 50km/h. In Doka's model this results in a noise type approval value of 74.16 dB. Such a vehicle has a generic noise damage of 1.811 micro-DALY (cf. Figure A.1 in Doka 2003).

[16] 1.811 micro-DALY are approximately 60 disability-adjusted life *seconds*. For each car-kilometre 60 seconds of life are collectively lost. At an assumed speed of 40 km/h of the car, one kilometre takes about 90 seconds to travel. Thus, the travel time of the car and the caused damage in life-years lost have surprisingly equal orders of magnitude. Each second travelled in a car steals approximately an equal amount of healthy life time from the public.

$$K_{DALY} = 184.74 \frac{\text{micro-DALY}}{\text{Swiss Francs of noise damage costs}}$$

Tab. 4.1 Noise damage factors for road and rail vehicles in micro-DALY per vehicle-kilometre.

Vehicle	**Noise damage in micro-DALY per vehicle-kilometre** micro-DALY/vkm
Car	1.811
Motorcycle	19.479
Moped	1.454
Public transportation bus	20.707
Coach	20.846
Light duty vehicles (LDV) <3.5 Gross-tons, Ger. 'Lieferwagen'	5.358
Heavy duty vehicles (HDV) >3.5 Gross-tons, Ger. 'Lastwagen'	17.610
Articulated lorry (semi-trailer truck), Ger. 'Sattelschlepper'	22.119
Passenger train	59.750
Freight train	106.623

Tab. 4.2 Noise damage factors for aircrafts in micro-DALY.

		Noise damage in micro-DALY for airplanes
1 average aircraft take-off	μ-DALY/1 movement	141'217.1
1 average aircraft landing	μ-DALY/1 movement	141'217.1
1 aircraft landing/take-off-cycle (LTO)	μ-DALY/LTO	282'434.3
1 short-range aircraft LTO	μ-DALY/LTO	106'586.34
1 long-range aircraft LTO	μ-DALY/LTO	603'487.19

Using loading factors, average occupancy (and for airplanes average distances travelled) these figures can be transformed into noise damages per person-kilometre or per ton-kilometre. Such figures can be found in the Appendix in Tab. A.6. The figures of Tab. 4.1 and Tab. 4.2 can be converted in to weighted damage factors for the Eco-indicator'99(HA) method with a factor of 25'970 EI99-points/DALY ($2.597 \cdot 10^{10}$ EI99-points/micro-DALY).

5 Results

Noise damages per service unit; passenger-kilometre or ton-kilometer, are displayed in the Appendix in Tab. A.5 and Tab. A.6. These results are compared here with other already established environmental damages of transport means, taken from the ecoinvent database v2.0. The results in the DALY scale are converted to Eco-indicator'99(HA)-points by multiplying with 25'970 EI99-points/DALY.

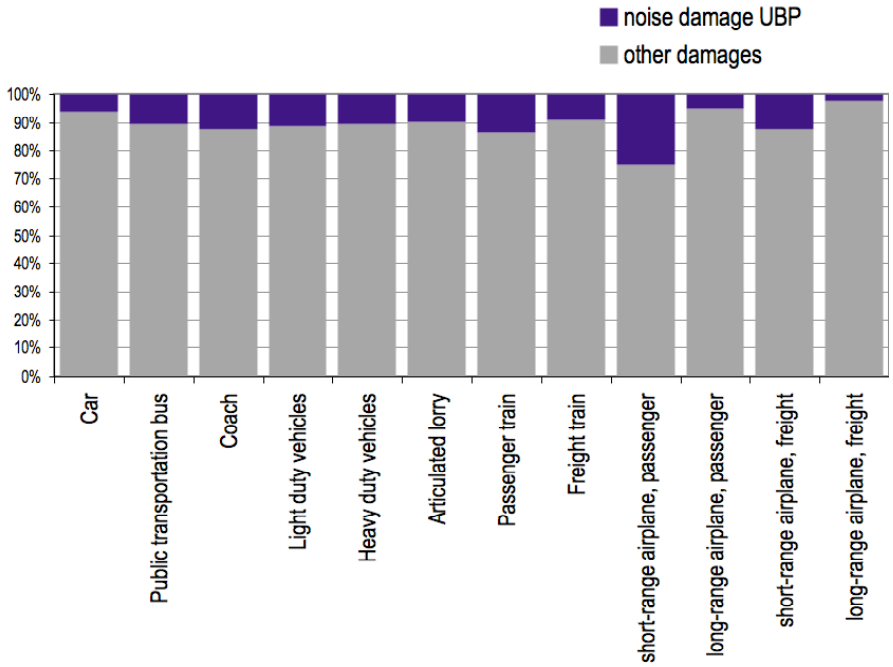

Fig. 5.1 Contribution of noise damages to total environmental burden in the ecological scarcity scale (UBP'97) for various transportation means.

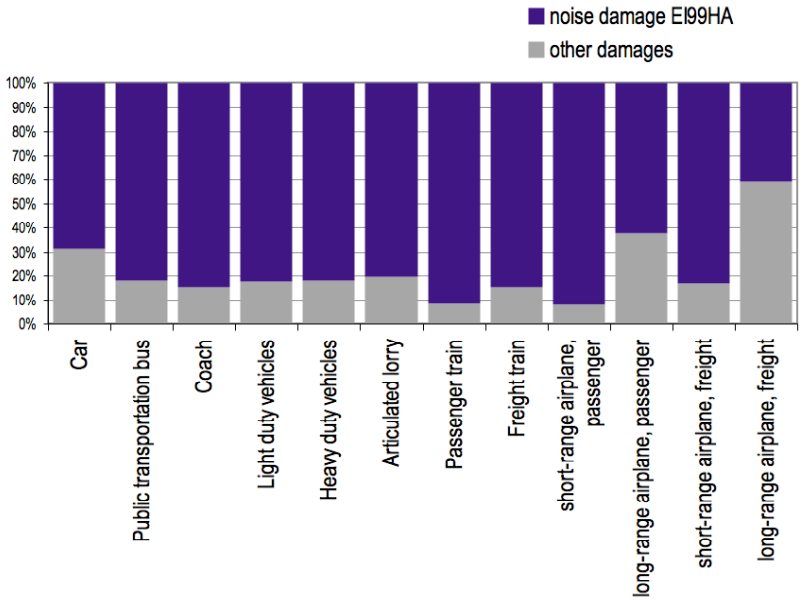

Fig. 5.2 Contribution of noise damages to total environmental burden (Eco-indicator'99HA-scale) for various transportation means.

The contribution of noise damages is perceptible in the ecological scarcity scale (Fig. 5.1) and makes up typically 9% of the total burden. Low contributions are for long-range airplane freight (2%); large contributions are for short-range airplane passenger transport (25%). Car noise as the most relevant source of traffic noise contributes 6% to the total LCA result for car transport.

The results in the Eco-indicator'99-scale look quite different (Fig. 5.2). Here noise damages are the *dominant* contribution; the only exception is long-range airplane freight with "only" 41% noise damage contribution. Short-range airplane passenger transport is entirely dominated by noise (92%). Car noise contributes 69% to the environmental damages of a car transport.

Both these results suggest that noise burdens are an important assessment gap in LCA, as pointed out in the introduction. However, the large discrepancy in the relevance of noise damages between the ecoscarcity scale and the Eco-indicator'99-scale are remarkable. As these are only first trans-modal estimates of noise damage, adjustments to these results are possible. For example, the utilised "exchange" value K_{DALY} of 184.74 micro-DALY per Swiss Franc, implicitly suggests that one DALY amounts to 5400 CHF (3600 EUR), or that a fatality at age 40 represents a monetary cost of about 200'000 CHF (130'000 EUR). This is well below the value of a statistical life (VSL) which is usually above 1 million CHF. For example, Sommer et al. [2004, p.155] consider the cost of a fatality of a 40-year old person in Switzerland to amount to at least 2.91 million CHF. If the value of health implied from ($1/K_{DALY}$) is too *small*, it is possible that the used value for K_{DALY} (in health damage per Swiss Franc) is too *large*. So it is possible that the results in the Eco-indicator'99-scale (Fig. 5.2) are exaggerated. On the other hand the results in the ecological scarcity scale (Fig. 5.1) are possibly too conservative. In this scale, the acceptable level of noise damage was defined at a situation where 25% of the Swiss population are highly annoyed by noise, based on Swiss noise regulations (see Doka 2003). A law that exposes 25% of the population to severe impairments seems a rather neglectful and unsustainable goal. It is therefore possible that the noise contributions in the ecological scarcity scale are underestimated.

6 The issue of including traffic noise into LCI databases

Traditionally in LCA emissions are recorded in the inventory stage (LCI) and valued in the Impact Assessment stage (LCIA). Emissions are usually interpreted as exchanges between the man-made technosphere and the surrounding biosphere (air, water, soil). For noise the actual physical quantity exchanged with the biosphere are temporary changes in air pressure, since sound is a perceptible change in air pressure. As a basic rule in LCA it is reasonable to keep the "biosphere" separate from the "techosphere" to avoid simplified assessments. In LCI the chain of technosphere effects shall be followed to the point where a contact with the biosphere actually occurs. For example the full process chain of electricity production shall be modelled in LCI, and not be cut short by inventorying "kWh electricity consumption" and assigning some burden to that parameter in *LCIA*. LCIA shall only deal with effects of emissions to the safeguard subjects like ecosystem quality, human health or resources.

The effect of any kind of emission is very dependent on its surroundings. This is true for "traditional" air pollutants such as NO_x or VOCs as well as for the "newcomer" noise. It is imaginable to inventory one single common physical noise parameter in LCI in attempting to asses noise damages, e.g. noise energy as noise-power-seconds or similar. It seems however that a lot of important information would be lost this way, for example a distinction between night and day. It is suggested here to start inventorying pure technosphere activities like vehicle-, passenger- or ton-kilometers of individual transport modes in LCI to ease the assessment of noise damages in LCA, e.g. "vkm car" or "tkm rail". Further distinctions e.g. into "car vkm at night" or "tkm rail in Portugal" are possible. These are not strictly biosphere exchanges, but this allows for more detailed treatment and yields more appropriate results than condensing noise biosphere exchanges into one common unit and assessing such a condensed parameter in LCIA generically. It allows also for more fine-tuned future development of noise LCIA [17]. In the rare cases, where the LCI already includes a detailed noise emission and exposure model, it is also imaginable that the LCI records not vehicle-kilometres, but noise-exposed persons.

[17] There is precedence of such pseudo-"biosphere exchanges" in the ecoinvent LCI database, for example for reservoir hydropower the biosphere exchange "Volume occupied, reservoir" was created, which indicates how much reservoir space is occupied (in m^3·years) for each kWh of energy.

7 Concluding remarks

This study presents estimates for inclusion of traffic noise damages into LCA. All figures are for *average* transport situations. As previous studies have shown, noise damages during the night are much larger per vehicle-kilometre than during the day [Müller-Wenk 1999 and 2002, Doka 2003]. This would invite a better distinction between night transport and day transport modes. However, in common LCA studies, transport processes are used as background processes only, and that level of detail is usually not available and the use of an average value is sufficient[18]. In the future a day/night distinction can be targeted, either using detailed exposure models or using other studies to derive a typical day/night split from the average value (similar to the splitting of average airplane noise into short- and long-range airplanes done in the Appendix).

Noise damage cost studies involve at some level noise exposure studies. As an (internal) intermediate result, the exposure of the population (persons per decibel noise class) are calculated. The author did not attempt to obtain those figures, but could do so in the future. For the use in LCA, these figures could be recalculated into DALYs or UBPs using known effect functions. With the current estimates, mismatches in methodology in the used sources [Sommer et al. 2004] and [Von Däniken et al. 2002] are possible. Using exposure data, effect functions and consistent disability weights increases transparency and consistency of these results.

As pointed out in 2.3 Ship noise on page 6, marine noise is not covered in this study. In the future effects of marine transport noise should be assessed as well.

[18] It might be known that e.g. a product is being transported over 50 km, but it is not known if that transport occurs during the day or during the night. Equally it is not known if the used truck is loaded up to capacity, or if traffic conditions are congested, all of which can affect the emissions per ton-kilometre. In LCA this ambiguities are usually dealt with using average values or, for foreground processes, with sensitivity analyses.

Appendix

The noise burden figures in chapters 3 and 4 are per traffic vehicle movement, in vehicle-kilometre or aircraft movement. Other units of transport services are common, like person-kilometre for passenger transport, or ton-kilometre for good transport. Results with these units are easily obtained, using average figures of passenger occupancy or load factors. For better transparency these parameters are presented here in order to facilitate adaptations to other boundary conditions.

Sommer et al. [2004] present results per vehicle kilometre and per person- or ton-kilometre. From that loading factors can be calculated, which are shown in Tab. A.1.

Tab. A.1 Load factors for road and rail vehicles

Vehicle		Load factors
Car	pers./veh.	1.6364
Motorcycle	pers./veh.	1.0769
Moped	pers./veh.	1
Public transportation bus	pers./veh.	12.364
Coach	pers./veh.	21
Light duty vehicles (LDV) <3.5 Gross-tons	tons/veh.	0.26389
Heavy duty vehicles (HDV) >3.5 Gross-tons	tons/veh.	5.6667
Articulated lorry (semi-trailer truck)	tons/veh.	11.333
Passenger train	pers./veh.	107.09
Freight train	tons/veh.	323.35

Air traffic is separated into two main categories: short-range/intra-European flights and intercontinental flights, as done in [Spielmann et al. 2007]. Spielmann takes the typical travel distances for these flights to be 500 and 6000 kilometres, respectively. Both kinds of flights transport passengers and freight in one vehicle. Spielmann et al. [2007, p.149] detail the typical passenger and freight load, as reproduced in Tab. A.2.

Tab. A.2 Data for passenger or freight airplane transport. Figures in brackets refer to percent of maximal capacity.

	Unit	Short-range flights	Intercontinental flights
Typical freight load	metric tons (% of max.capacity)	1 (8%)	25 (35%)
Typical number of passengers	passengers (% of max. capacity)	65 (65%)	320 (80%)
Average distance	km per flight	500	6000
Freight transport per flight	ton-km per flight	250	75'000
Passenger transport per flight	pers.km per flight	16'250	960'000

Since one airplane noise event (landing or take-off) can be attributed to *two* delivered services, passenger and freight transport, an allocation between the two is necessary. Here, the allocation scheme in [Spielmann et al. 2007, p.168] is adopted, see Tab. A.3. These figures reveal that e.g. the motivation for a short-range flight is mostly (94%) passenger transport. Accordingly 94% of the noise

burden from a short-range take-off will be attributed to the passenger transport (the 16'250 pers.km from Tab. A.2) and only 6% to freight transport (250 ton-km).

Tab. A.3 Allocation figures for passenger or freight airplane transport.

	Short-range flights	Intercontinental flights
Allocation to freight transport function	6.0%	24.6%
Allocation to passenger transport function	94.0%	75.4%

The noise levels of different airplanes are not distinguished in [Sommer et al. 2004]. Mainly due to size, long-range airplanes typically have 7.53 dB louder movements than the smaller short-range airplanes (based on data in Hochfeld et al. 2004). This means that per movement a long-range airplane causes about a factor 5.66 more noise damages than a short-range airplane[19]. The typical share of air traffic is 65% short-range movements and 35% long-range movements (calculated from Spielmann et al. 2007). This implies that a short-range plane is only 38% as damaging as the *average* plane; but a long-range plane is a factor 2.14 more damaging than the average plane[20].

Tab. A.4 shows the attribution of a LTO noise damage event to the delivered airplane transport services. This is a combination of Tab. A.2 and Tab. A.3 and the 38%÷214% distinction derived above. For example, for a short-range flight 94% of the noise burdens are allocated to passenger transport, the typical passenger transport service delivered by a short-range flight is 16'250 pers.km and a short-range flight is only 38% as damaging as the average plane. Thus for each pers.km of a short-range flight, a fraction of $2.18302 \cdot 10^{-5}$ of an average LTO noise damage can be attributed (= 1 LTO · 94% · 38% /16'250 pers.km). These figures can be used to convert the average LTO damages of Tab. 2.2 (page 5) and Tab. 4.2 (page 10) to differentiated damage factors.

[19] The decibel scale is a logarithmic measure of the noise energy. A noise 7.53 dB louder has a factor 5.66 more energy, as $10^{(7.53/10)} \cong 5.66$.

[20] These figures are based on the modal split of short-range (f_S) vs. long-range movements (f_L) in average airplane movements ($f_S \div f_L$ = 35%÷65%) and the figure of 5.66 (K) more noise damage for a long-range movements. If the *average* flight movement has a noise damage of D_A (in CHF, UBP or DALY) then the noise damage of a *long-range* movement D_L is
$D_L = D_A/(f_S/K + f_L) =$
$D_A/(35\%/5.66 + 65\%) =$
$D_A/0.466 =$
$D_A \cdot 2.144 = D_L$.
The noise damage of a *short-range* movement D_S is then
$D_S = D_L/K =$
$D_A \cdot 2.144/5.66 =$
$D_A \cdot 0.3774 = D_S$.
As control, the noise damage of an average movement D_A is
$D_A = (f_S \cdot D_S + f_L \cdot D_L) =$
$(35\% \cdot D_A \cdot 0.3774 + 65\% \cdot D_A \cdot 2.144) =$
$(0.244 \cdot D_A + 0.756 \cdot D_A) =$
D_A ✓.

Tab. A.4 Fractional attribution of a LTO noise damage event to the delivered airplane transport services. frac. = fraction

Damage fraction per service unit	unit	Short-range flights [1]	Intercontinental flights [1]
LTO damage fraction on passengers	LTO frac. / pers.km	$2.18302 \cdot 10^{-5}$	$1.67823 \cdot 10^{-6}$
LTO damage fraction on freight	LTO frac. / ton-km	$9.05723 \cdot 10^{-5}$	$7.00849 \cdot 10^{-6}$

1 Figures in table are calculation results, without progressive rounding errors.

The following tables give the results for the average occupancies, load factors and attributions above. Obviously, the results are sensitive to these boundary conditions, which are quite variable. Surprisingly, for example, the noise damage from a public transportation bus per person-kilometre exceeds the damage from a car. This the combined effect of a larger and hence louder vehicle but a occupancy of only 12 passengers per bus (Tab. A.1). This bus occupancy seems rather small for a bus, but might be explained by a large share of mileage with low occupancy in rural settings. The result for a coach (occupancy 21 persons) on the other hand is roughly equal to the car.

We can also observe an economy-of-scale-effect in road freight transport. The small light duty vehicles cause more noise damage per ton-kilometre than the large articulated lorries, although on a vehicle basis – and this corresponds to the direct impression of an actual observer on the side of the road – the latter causes 4 times more noise damage. But , the latter also transports a factor 40 more goods and ends up beings less burdening per mass of transported freight.

It is also important to remember that noise burdens are only a part of the total environmental damage of a transport vehicle and means of transport should not be judged on noise damage alone.

Tab. A.5 Noise damage factors for the environmental scarcity method per service-kilometre (red = passenger transport, blue = freight transport).

Vehicle	unit	Noise damage factor for environmental scarcity UBP
Car	UBP/pers.km	8.981
Motorcycle	UBP/pers.km	146.765
Moped	UBP/pers.km	11.796
Public transportation bus	UBP/pers.km	13.590
Coach	UBP/pers.km	8.054
Light duty vehicles (LDV) <3.5 Gross-tons	UBP/ton-km	164.753
Heavy duty vehicles (HDV) >3.5 Gross-tons	UBP/ton-km	25.216
Articulated lorry (semi-trailer truck)	UBP/ton-km	15.836
Passenger train	UBP/pers.km	4.527
Freight train	UBP/ton-km	2.676
Short-range airplane, 500km (passengers)	UBP/pers.km	50.029
Long-range airplane, 6000km (passengers)	UBP/pers.km	3.846
Short-range airplane, 500km (freight)	UBP/ton-km	207.566
Long -range airplane, 6000km (freight)	UBP/ton-km	16.061

Tab. A.6 Noise damage factors in micro-DALYs per service-kilometre (red = passenger transport, blue = freight transport).

Vehicle	unit	**Noise damage factor in micro-Daly**
Car	μ-DALY/pers.km	1.1069
Motorcycle	μ-DALY/pers.km	18.0876
Moped	μ-DALY/pers.km	1.4538
Public transportation bus	μ-DALY/pers.km	1.6749
Coach	μ-DALY/pers.km	0.9926
Light duty vehicles (LDV) <3.5 Gross-tons	μ-DALY/ton-km	20.3044
Heavy duty vehicles (HDV) >3.5 Gross-tons	μ-DALY/ton-km	3.1076
Articulated lorry (semi-trailer truck)	μ-DALY/ton-km	1.9517
Passenger train	μ-DALY/pers.km	0.5579
Freight train	μ-DALY/ton-km	0.3297
Short-range airplane, 500km (passengers)	μ-DALY/pers.km	6.1656
Long-range airplane, 6000km (passengers)	μ-DALY/pers.km	0.4740
Short-range airplane, 500km (freight)	μ-DALY/ton-km	25.5807
Long -range airplane, 6000km (freight)	μ-DALY/ton-km	1.9794

The figures of Tab. A.6 can be converted in to weighted damage factors for the Eco-indicator'99(HA) method with a factor of 25'970 EI99-points/DALY ($2.597 \cdot 10^{10}$ EI99-points/micro-DALY).

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