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Modified life cycle assessment for Low-Noise urban roads including acoustics and monetarization

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A R T I C L E I N F O

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A B S T R A C T

The evaluation of environmental impacts for low-noise roads is a challenging topic in life cycle assessment (LCA) due to noise reduction considerations. This paper presents hybrid modifications of conventional LCA, using acoustical pavement characterization data from the close proximity (CPX) test, and models of noise emission, propagation and exposure to incorporate the inventories and impacts of road traffic noise. Furthermore, based on the system and indicators considered in LCA, the monetarization of direct and external costs of low-noise roads was included, in order to extend environmental interpretation to a monetary perspective. The modified LCA was applied in a realistic road test section, comparing (1) traditional stone mastic asphalt (SMA) with low-noise semi-dense asphalt (SDA) surfaces, and (2) different strategies for using SDA. The results of the test section indicated the significant role of road traffic noise in human health impacts, that translate to economic benefits for using low-noise pavements.

1. Introduction

The expansions of road traffic and transportation as a result of accelerated economic activities, inevitably lead to increasing road traffic noise. Road traffic noise has been a major source of high annoyance and high sleep disturbance in the urban areas having a detrimental effect on human health (Basner and McGuire, 2018; Guski et al., 2017; WHO Europe, 2018). To cope with this problem, low-noise pavements were developed to mitigate the contribution from tire/road interaction, which is the dominant source of road traffic noise at medium or high vehicle speeds (Clar-Garcia et al., 2016; Poulikakos et al., 2022). The acoustical performance of low-noise pavements are usually regularly monitored in the field, where the most popular methods are close proximity (CPX) and statistical pass-by (SPB) tests (ISO 11819-1, 1997; ISO 11819-2, 2017). These methods aim to observe acoustical ageing, which usually occurs during the service life of low-noise pavements (Gardziejczyk, 2016). Due to high porosity, low-noise pavements have poor mechanical performance (Mikhailenko et al., 2020). Although polymer-modified binders are usually used to improve the durability, the service life of low-noise pavements is still shorter compared to dense asphalt pavements (Lyu et al., 2021; Zhang et al., 2020).

Considering the strengths and weaknesses of low-noise pavements, it is worthwhile to quantify their environmental impacts to support decision making regarding pavement strategies. Several studies (Blaauw et al., 2022; Chen et al., 2021; Farina et al., 2017; Piao

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et al., 2022a) have conducted life cycle assessment (LCA) to evaluate the environmental impacts of pavements, especially considering the use of alternative materials. LCA focuses on the whole life cycle of a product, from the raw materials production to the end-of-life (ISO 14040, 2006; ISO 14044, 2006). As a result, LCA is able to identify the possible burden-shifts, drawing comprehensive conclusions on a particular scenario (Hellweg and Milà i Canals, 2014). Noise has impacts on both the environment and society (Gompf et al., 2020, 2022), with recommendations as an indicator for the sustainability assessment of road (CEN, 2016). However, the traditional LCA methodology may not be suitable due to the lack of noise considerations (Müller-Wenk, 2004). Since low-noise pavements reduce the sound level at the cost of shortened service life, the traditional LCA would not deliver fair results by excluding the inventory and impacts of noise (Piao et al., 2022b).

To include noise in LCA, some modifications of traditional LCA methodology have been proposed: for example, based on a set of archetypal situations, Cucurachi et al. (2012) considered all types of noise and used linear sound power instead of logarithmic decibel (dB) to calculate characterization factors, simplifying the integration of noise impacts from different sources. They proposed a specifically defined indicator in "person × Pa * s", implying noise exposure of people within a period of time, to describe the noise impacts on humans (Cucurachi and Heijungs, 2014). The challenge of this method is, however, to compare the specifically defined indicator with other international indicators of human health, such as disability adjusted life years (DALY) (Heijungs and Cucurachi, 2017). For the LCA of low-noise pavements, it may not be necessary to consider all the noise sources, while the major concern is road traffic noise. This was investigated by several LCA studies (Althaus et al., 2009; Franco et al., 2010; Müller-Wenk, 2004), including the calculation of road traffic noise using emission models, the quantifications of noise exposure and the resulting human health impacts. These studies assumed a 1:1 correlation between the noise at source and receivers, which disregards the consideration of propagation of noise. Their results were expressed in DALY, which had an added advantage that it can be compared or integrated with other human health impacts. Nevertheless, the impact assessments presented in these works were based on the difference of noise level between the scenarios, thus the results presented the variation rather than the absolute impact of each scenario. In addition, due to the non-linear properties of noise emissions and dose–response relations, the linear approximation in these studies limited the extrapolation of results to situations with large variations. Lastly, the sound levels in these papers were determined for a uniform pavement but at different traffic conditions, which did not allow to assess various pavement types.

Considering the methodologies and research gaps of the noise-LCA studies from various researchers above, our recent study (Piao et al., 2022b) aimed at more reliably including the acoustical aspects in LCA with a focus on low-noise pavements. Specifically, the environmental impacts of semi-dense asphalt (SDA), a type of low-noise pavement surface, were compared with that of the traditional dense stone mastic asphalt (SMA). The study applied the road traffic noise emission model sonROAD18 (Heutschi et al., 2018),

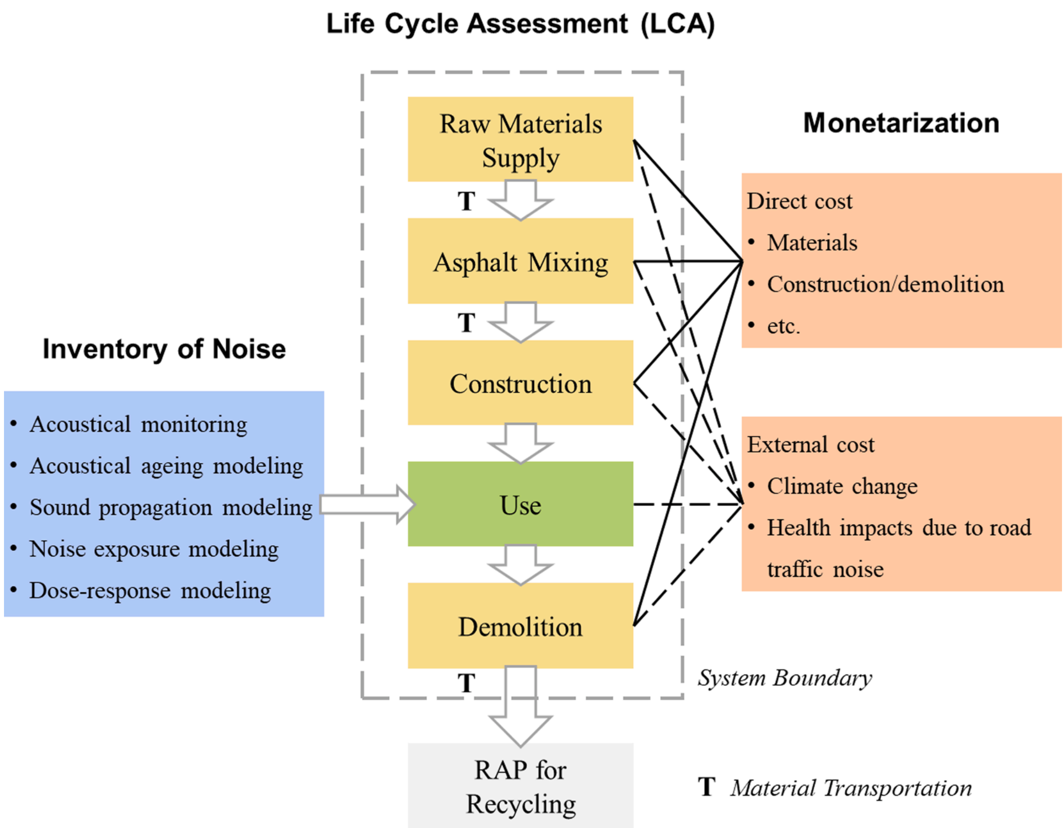

Fig. 1. Methodology framework of this research (RAP: reclaimed asphalt pavement).

considering the same traffic condition but different pavement correction terms for SMA and SDA, to calculate the equivalent sound pressure level (L_{eq}) at 1 m distance from the vehicles for each scenario. Inspired by previous publications (Althaus et al., 2009; Franco et al., 2010; Müller-Wenk, 2004), the change of sound level at the source was assumed to translate 1:1 to the level change at the receivers which made a recalculation of the propagation effects redundant. The difference of road traffic noise between SMA and SDA was applied in the original noise exposure data, in order to derive the noise exposure if all the traditional pavements were replaced by SDA. In a second step, the latest dose–response curves (Brink et al., 2019a; Brink et al., 2019b) were applied to estimate the proportion of population with health problems due to road traffic noise, and furthermore, to quantify the health impacts in DALY. Since noise exposure data were determined separately for each scenario, the dose–response curves can be applied directly without using a linear approximation and incremental values. Therefore, the results were expressed in absolute DALYs for SMA and SDA at a given traffic load, which can not only compare the total health impacts of different scenarios, but can also compare the health impacts between noise and other pavement processes (raw materials, mixing, construction and demolition).

Although some of the research gaps (such as integration and interpretation of noise results, absolute health impacts of scenarios and linear approximation of dose–response curves) were addressed in Piao et al. (2022b), new challenges and gaps could also be identified. For example, the pavement factor for calculating road traffic noise was based on the recommended values of the sonROAD18 model, while the data from field testing (CPX and SPB), which reveal the acoustical performance of the specific pavements, were not considered. Besides, the assumption of a 1:1 correlation between source and receivers of noise is suitable if noise reduces at a large scale of the road network, but it would be less accurate for a specific local condition with both conventional and low-noise pavements. Moreover, in Piao et al. (2022b), the net benefit and impact of low-noise pavements compared to dense pavements were presented in terms of different environmental indicators, such as human health impacts (net benefit), greenhouse gases emissions (net impact) and non-renewable cumulative energy demand, revealing trade-offs that are difficult to resolve. Therefore, the objective of this paper is to address these new research gaps, proposing further modifications based on Piao et al. (2022b) to conduct LCA of low-noise SDA pavement surfaces. As shown in Fig. 1, for the inventory analysis of noise, a method is presented using the CPX data from acoustical monitoring as the pavement factors of noise emission model (sonROAD18). This aims to improve the accuracies of pavement effects on the road traffic noise. Furthermore, instead of assuming a 1:1 correlation between the noise source and receivers, this paper applies a sound propagation model following ISO 9613-2 (1996) to determine the sound level at buildings surrounded by a mix of conventional and low-noise roads. Finally, based on the functional unit, system and impact indicators of LCA, a monetarization method is proposed to estimate the direct and external costs of all the LCA processes. This supports the conversion of the strengths and weaknesses of low-noise pavements into monetary units, extending the interpretation of LCA and integrating various impact indicators. As an example, the methodology framework in Fig. 1 was applied in a test section of SDA in the Canton of Zurich, Switzerland, considering the local traffic, climate and geographical conditions. For a comparative analysis, SMA was used as the reference pavement surface. Two operational scenarios of SDA, including the use of SDA for 10 and 15 years, were also evaluated. This is because the current service life of SDA (10 years) is solely based on the acoustical durability (FEDRO and FOEN, 2008), while current field data indicate that the mechanical lifespan could be longer. Hence, there is a possibility to extend the service life of SDA for additional years with limited noise reduction. This can be assessed by LCA allowing to demonstrate whether the acoustical performance should be the only determinant for the service life of SDA.

2. Life cycle assessment (lca)

This section describes the life cycle assessment of different pavement scenarios, with goal and scope definition, inventory analysis and impact assessment.

2.1. Goal and scope definition

The goal of this LCA is to quantify the environmental impacts of conventional and low-noise pavement surfaces, considering road traffic noise during the use phase of pavements. The conventional dense pavement surface used here is SMA with a maximum aggregate size of 11 mm, the low-noise semi-dense surface course is SDA with a maximum aggregate size of 4 mm.

2.1.1. Functional unit

The functional unit (FU) was a segment of an urban pavement surface with a length of 700 m, a width of 7.5 m (two lanes) and a thickness of 30 mm, supporting the traffic load labeled as T4 (300 – 1000 equivalent single axle loads per day) for 30 years under average climatic conditions in Switzerland (Type B). The pavement thickness for the traffic load and climate were determined according to the Swiss standard (SN 640-430c, 2014) for SMA and SDA. Constant traffic volume was assumed with a speed of 50 km/h, which is the average value in Swiss urban roads (Catillaz and Fischer, 2018). As indicated by SN 640-430c (2014), when considering the traffic load of T4 and climatic condition of Type B, both SMA and SDA have the same structure i.e. binder and base courses. Hence, it was only necessary to consider the surface course affecting different mechanical and acoustical performance in this LCA.

2.1.2. Investigated scenarios

Three scenarios were compared in this paper, namely (1) SMA with a service life of 20 years, (2) SDA with a service life of 10 years, and (3) SDA with a service life of 15 years. The functional unit implies 1.5 life cycles for SMA, 3 and 2 life cycles for SDA (10 years) and SDA (15 years), respectively. The three scenarios evaluated not only show the difference between conventional and low-noise pavement surfaces, but also provide insight into different operational strategies of low-noise pavement surfaces.

2.1.3. System boundary

As shown in Fig. 1, five processes covering the life cycle of pavements were considered in this LCA. The raw materials included natural aggregates and polymer-modified asphalt binder. The asphalt mixing included the transportations of raw materials from the suppliers to the plant, followed by the manufacturing of asphalt mixtures in the plant. The construction consisted of transporting asphalt mixtures from the plant to the working site, followed by the processes of paving and rolling. The use phase included the emission and propagation of road traffic noise. The demolition implied removing the used pavement surface, at the end of its service life, and transporting the reclaimed asphalt pavements (RAP) back to the mixing plant.

2.2. Inventory analysis

This section explains the inventories of LCA processes in Fig. 1. The quantification of road traffic noise was included in the inventory of the use phase. Since the ecoinvent (2022) database was widely applied in this LCA, it should be noted that all the ecoinvent (2022) datasets were based on version 3.8 cut-off.

2.2.1. Raw materials

The mix design and material information of the three scenarios are listed in Table 1. The volume was defined by the FU, considering the length, width and thickness of the pavement surface and the number of new pavements to be constructed during the service life. The bulk densities were measured from the pavement cores of the test sections. The binder contents were based on the declarations of the mixing plant, using polymer-modified binder for all the three scenarios.

The inventory of aggregates was obtained from "Gravel, crushed CH| production | Cut-off, U" of the ecoinvent database. The inventory of polymer-modified binder was based on the Eurobitume reports (Eurobitume, 2012, 2020), considering the crude oil extraction and following transportation to Europe, the production and storage of base binder by the refinery, the production, milling of polymer (styrene butadiene styrene) and the mixing with base binder.

2.2.2. Asphalt mixing

The asphalt mixing referred to the transportations of aggregates and asphalt binder from the suppliers to mixing plant, along with energy consumption, equipment use and emissions to air during the mixing. By consulting with the mixing plants, the natural aggregates were provided domestically and the average transportation distance was 50 km by lorry, the polymer-modified binder was imported from the surrounding countries (Germany, France and Italy) with an average distance of 100 km by lorry. All the lorries had a loading capacity of 25 metric tons and total weight of 40 metric tons. The ecoinvent dataset "Transport, freight, lorry $>$ 32 metric ton, euro6 RER| market for transport, freight, lorry $>$ 32 metric ton, EURO6 | Cut-off, U" was used as the inventory of transportation.

The energy consumption during mixing was based on the information from local mixing plants, using 8.6 kWh electricity and 216 MJ natural gas per metric ton of mixtures. These are average values based on the overall energy consumptions and total asphalt production of the plant. The inventories of electricity and natural gas followed the ecoinvent datasets "Electricity, medium voltage CH| market for | Cut-off, U", and "Heat, district or industrial, natural gas CH| market for heat, district or industrial, natural gas | Cut-off, U", respectively. The equipment was based on the ecoinvent dataset "Mastic asphalt CH| production | Cut-off, U", assuming that the lifespan of machines was 20 years and the yearly production of mixtures was 150 000 metric tons. The machine inventories are "Conveyor belt GLO| market for | Cut-off, U" and "Industrial machine, heavy, unspecified RER| market for industrial machine, heavy, unspecified | Cut-off, U" from the ecoinvent.

The emissions to air during mixing also followed the ecoinvent dataset "Mastic asphalt CH| production | Cut-off, U", including the emissions of Benzo(a)pyrene and non-methane volatile organic compounds. However, since the ecoinvent dataset applied a binder content of 8 %, which was higher than the contents in the binder used in this LCA (6 % – 6.4 %). We assumed that the emissions to air during the mixing were proportional to the binder content, thus the air emissions from the binder content were adjusted from 8 % to 6 % – 6.4 %.

2.2.3. Construction and demolition

As indicated in Piao et al. (2022a), the pavement construction referred to the paver, material transport vehicle, roller and generators with diesel consumptions of 4.8, 4.5, 12.9 and 11.9 MJ per metric ton of asphalt mixture, respectively. Prior to the construction work, the asphalt mixture was transported from the mixing plant to the paving site, assuming the distance as 50 km (the longest

Table 1
Mix design and material information of the three scenarios.

	SMA (20 years)	SDA (10 years)	SDA (15 years)
Maximum aggregate size [mm]	11	4	4
Porosity [%]	3.4	12	12
Volume [m^3/FU]	236	473	315
Bulk density [t/m^3]	2.4	2.1	2.1
Binder content [%]	6.4	6	6
Asphalt mixture [t/FU]	559	1014	675
Aggregates [t/FU]	523	953	635
Asphalt binder [t/FU]	36	61	40

distance for a plant to transport asphalt mixtures in Switzerland) using the same type of lorry as that in Section 2.2.2. The demolition required the milling machine and generators with diesel consumptions of 11.5 and 4.8 MJ per metric ton of asphalt mixtures, followed by the transportation of RAP from the working site to the mixing plant. The inventories of diesels were obtained from the ecoinvent datasets "Diesel, burned in building machine GLO| market for | Cut-off, U" and "Diesel, burned in diesel-electric generating set, 10 MW GLO| market for | Cut-off, U" for machines and generators, separately.

2.2.4. Use phase

The inventory analysis of the use phase focused on quantifying the emission and propagation of road traffic noise, as well as the resulting number of people potentially having health problems. The following sections present three steps using the acoustical testing in the field and various modeling methods.

2.2.4.1. Road traffic noise emission. To monitor the acoustical performance of asphalt pavements in the field, the CPX method following ISO 11819-2 (2017) is widely used (Mikhailenko et al., 2020). CPX is a cost-effective method to observe the acoustical characteristics of tire/road interactions for the pavement sections. The measurement evaluates the sound pressure in the near-field of two reference tires (representative for passenger cars and heavy vehicles) that are mounted on a trailer that is in tow of a passenger car. The measurements are usually conducted at the nominal speeds 50 and 80 km/h. Deviations from the nominal speed, temperature effects as well as ageing of the tires are considered by normalizing the data to reference values. The direct testing result is a "CPX index" that represents the absolute sound pressure level at a distance of 20 cm from the test tires. In Switzerland, the CPX index is usually converted to the indicator KB [dB(A)] that describes the correction to be applied to the national standard emission model StL-86+ (FOEN, 1987). Eq. (1) and Eq. (2) are examples of conversion at the reference speed of 50 km/h.

$$KB_{50km/h,P} = 1.2468 \bullet CPX_P - 112.3 \tag{1}$$

$$KB_{50km/h,H} = 1.3617 \bullet CPX_H - 126.16 \tag{2}$$

where CPX_P [dB] and CPX_H [dB] are the CPX indices for the tires representing passenger cars and heavy vehicles, respectively. KB [dB (A)] can be interpreted as the difference of tire/road noise compared to a reference pavement surface without noise mitigation. More details of conversion can be found in FEDRO (2013).

With low-noise pavements, the effect typically declines over the years (Cao et al., 2020). There are several reasons for acoustical ageing. The mechanisms are not yet fully understood, but clogging of the pores by dirt and the deformation of the pore structure due to traffic are among the causes (Bühlmann et al., 2015; Bühlmann and Hammer, 2017). Several models have been proposed to describe acoustical ageing, using linear, exponential and logarithmic time dependencies (Licitra et al., 2019). In Switzerland both exponential and logarithmic models have been applied (Hammer et al., 2015). The SDA test section in this paper has been in use for four years, applying the method from Bühlmann et al. (2019) which improved acoustic factors by reducing sand and filler contents (called SDA 4–12/16). Since CPX measurements were for the first four years, these data were included in an exponential model to estimate acoustical ageing, as shown in Eq. (3).

$$KB_{50km/h,mix,X} = C_1 \bullet exp[C_2 \bullet (X-1)] + C_3 \tag{3}$$

where $KB_{50km/h,mix,X}$ [dB] is the above introduced pavement indicator for a reference speed of 50 km/h and mixed traffic volume (92 % of light vehicles and 8 % of heavy vehicles) in the service year X ($X = 1 - 15$). C_1, C_2 and C_3 are fitting parameters. Fig. 2 shows the $KB_{50km/h,mix,X}$ [dB] values derived from the CPX test and the acoustical ageing model in this paper, with fitting parameters of C_1 = -5.37, C_2 = -0.21 and C_3 = -0.77.

The $KB_{50km/h,mix,X}$ [dB] indicates the pavement specific correction of road traffic noise based on the model StL-86 + that has been

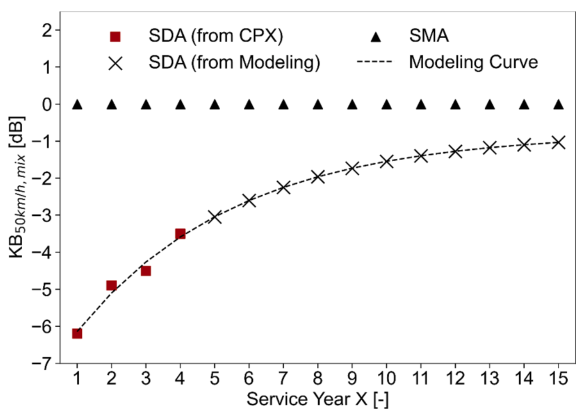

Fig. 2. $KB_{50km/h,mix}$ [dB] determined from the CPX test and the applied acoustical ageing model. For SMA, $KB_{50km/h,mix}$ [dB] was assumed to be zero.

developed for the vehicle fleet that on the roads in the 1980 s (FOEN, 1987). In order to adapt the calculations to the present-day fleet, we applied the sonROAD18 model (Heutschi et al., 2018), which is based on the common noise assessment methods in Europe (Kephalopoulos et al., 2012), specifying the emission strengths for the vehicle classification scheme used in Switzerland (SWISS10). The specification of a pavement can be based on *KB* [dB] values derived from CPX-measurement data. More details of this model can be found in Heutschi et al. (2018). In our application, the input data included the hourly traffic volume for SWISS10 categories, $KB_{50km/h,mix,X}$ [dB] values, temperature (10 °C) and vehicle speed (50 km/h). The corrections for vertical directivity, inclination of the road and special tires were assumed to be zero. The output $L_{eq,s,t,X}$ [dB(A)] was the A-weighted average equivalent sound pressure level during the hour t at a distance of 1 m from the sources. This paper defined t = 6:00 – 22:00 and t = 22:00 – 6:00 as daytime and nighttime, respectively. Eq. (4) and Eq. (5) calculate the day (*D*) and night (*N*) equivalent sound pressure levels of a pavement surface.

$$L_{eq,s,D,X} = 10 \bullet lg\left(\frac{1}{16} \bullet \sum_{t=6}^{21} 10^{0.1 \bullet L_{eq,s,t,X}}\right) \tag{4}$$

$$L_{eq,s,N,X} = 10 \bullet lg\left(\frac{1}{8} \bullet \sum_{t=22}^{5} 10^{0.1 \bullet L_{eq,s,t,X}}\right) \tag{5}$$

2.2.4.2. Calculation of noise level at the receiver position. Road traffic noise only becomes a nuisance when it reaches residents. With the emission of the relevant road segments with correction for vertical directivity as a starting point, the sound pressure levels at the residents homes were calculated. In this LCA, the standard ISO 9613-2 (1996) was used as a propagation model. Eq. (6) shows the considered attenuation terms:

$$L_{eq,r,D/N,X} = L_{eq,s,D/N,X} - \left(A_{div} + A_{atm} + A_{gr} + A_{bar} + A_{misc}\right) \tag{6}$$

where $L_{eq,r,D/N,X}$ [dB(A)] is the sound pressure level at the receiver location **r**, caused by a certain road segment **s**. For SDA pavements,

Fig. 3. Illustrations of the SDA test section in orange and influenced buildings marked by circles. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

$L_{eq,s,D/N,X}$ [dB(A)] was calculated considering the $KB_{50km/h,mix,X}$ [dB] values in Fig. 2. For road segments with a standard pavement, $KB_{50km/h,mix,X} = 0$ was used to determine $L_{eq,s,D/N,X}$ [dB]. A_{div} [dB], A_{atm} [dB], A_{gr} [dB], A_{bar} [dB], A_{misc} [dB] are sound attenuations due to geometrical divergence, atmospheric absorption, ground effect, barrier and miscellaneous other effects, respectively. The details for calculating each attenuation component can be found in ISO 9613-2 (1996). The input data included the situation geometry, the category of reflecting surfaces, the ground factor, air temperature and relative humidity, using the software SLIP20. The total sound pressure level at a receiver location $L_{eq,r,tot,D/N,X}$ [dB(A)] is the aggregation of $L_{eq,r,D/N,X}$ [dB(A)] from all the surrounding road segments (Eq. (7)).

$$L_{eq,r,tot,D/N,X} = 10 \bullet lg\left[\sum_{i=1}^{n} 10^{0.1 \bullet L_{eq,r,D/N,X}(i)}\right] \tag{7}$$

where n is the total number of road segments that have acoustical impact on the receiver. $L_{eq,r,D/N,X}(i)$ is the sound pressure level after sound propagation from the segment i. Fig. 3 illustrates the locations of the SDA test sections and the other standard pavements as assumed in the calculations of this paper, together with 130 buildings that can profit from the noise reduction of SDA. The selection of the 130 positions was based on the criterion that the reduction of the receiver levels by the installation of the SDA pavement was at least 1 dB(A) in the first service year.

2.2.4.3. Number of people with potential health problems. In this step, the number of people with potential health problems due to road traffic noise was determined based on the sound pressure level ($L_{eq,r,tot,D/N,X}$ [dB(A)]) and the population of the affected buildings (Fig. 3), as well as the most recent dose–response curves. In detail, the studied health problems were high annoyance and high sleep disturbance, which are considered the most relevant impacts of road traffic noise (Kim et al., 2012). The dose–response curves were based on the SiRENE (Short and Long Term Effects of Transportation Noise Exposure) studies (Brink et al., 2019a; Brink et al., 2019b), which conducted mix-mode surveys and statistical analysis in Switzerland. Eq. (8) and Eq. (9) calculate the number of people with high annoyance (HA_X) and high sleep disturbance (HSD_X) in the service year X.

$$HA_X = \sum_{j=1}^{130} \frac{P(j)}{1 + exp\left(-\left(-8.4495 + 0.1115 \bullet L_{eq,r,tot,D,X}(j)\right)\right)} \tag{8}$$

$$HSD_X = \sum_{j=1}^{130} \frac{P(j)}{1 + exp\left(-\left(-7.1315 + 0.0976 \bullet L_{eq,r,tot,N,X}(j)\right)\right)} \tag{9}$$

where $L_{eq,r,tot,D,X}(j)$ and $P(j)$ are the sound pressure level and total number of people in building j. "130″ is the number of buildings influenced by the SDA test section (Fig. 3).

2.3. Impact assessment

The impact assessment refers to the environmental indicators for the conventional LCA and road traffic noise. The conventional indicators included the climate change using global warming potential for 100 years in kg CO_2-eq (IPCC, 2021), and non-renewable cumulative energy demand in MJ (Boustead and Hancock, 1979). These two indicators have been found to often correlate with several other environmental impacts for LCA (Steinmann et al., 2016). In addition, the human health impacts of the raw material productions, mixing, construction and demolition were quantified by the ReCiPe method with the endpoint category of "damage to human health" (including the effects from the midpoint impact categories of global warming, human health, stratospheric ozone depletion, ionizing radiation, ozone formation human health, fine particulate matter formation, human carcinogenic toxicity, human non-carcinogenic toxicity and water consumption human health). The reason for using this method is that the final results are presented in DALY, which can be further compared and integrated with the impacts of road traffic noise.

Based on the inventory in Section 2.2.4, the impacts of potential health problems due to road traffic noise were assessed in DALY. In this paper, we assumed that road traffic noise was not fatal for receivers, thus the "years of life lost" was not considered and only the "years lived with disability" was calculated. Eq. (10), Eq. (11) and Eq. (12) calculate the human health impacts (*HI*) of noise for the scenarios of SMA, SDA (10 years) and SDA (15 years). DW_{HA} and DW_{HSD} are disability weight factors of high annoyance and high sleep disturbance. According to Fritschi et al. (2011), the values of DW_{HA} and DW_{HSD} in Europe were recommended as 0.02 and 0.07, respectively. "1″ indicates one service year.

$$HI_{SMA} = \sum_{X=1}^{30}\left(HA_{X,SMA} \bullet DW_{HA} \bullet 1 + HSD_{X,SMA} \bullet DW_{HSD} \bullet 1\right) \tag{10}$$

$$HI_{SDA,10years} = 3 \bullet \sum_{X=1}^{10}\left(HA_{X,SDA} \bullet DW_{HA} \bullet 1 + HSD_{X,SDA} \bullet DW_{HSD} \bullet 1\right) \tag{11}$$

$$HI_{SDA,15years} = 2 \bullet \sum_{X=1}^{15}\left(HA_{X,SDA} \bullet DW_{HA} \bullet 1 + HSD_{X,SDA} \bullet DW_{HSD} \bullet 1\right) \tag{12}$$

3. Monetarization

This section compares the three scenarios from the economic perspective, namely (1) the direct cost of producing, constructing and reclaiming pavement surfaces, and (2) the external cost by monetarizing the environmental impacts of LCA. The currency was Swiss Franc in 2018 (the year when the road test sections was constructed) with 1 $CHF_{2018} = 1.02\ USD_{2018}$. The inflation rate from 2018 to 2021 was considered as 0.2 %, according to the inflation calculator for Switzerland.

3.1. Direct cost

The direct cost information was based on the communications with the industrial partners in Switzerland in the period 2021 – 2022. The cost of asphalt mixture consisted of the expenditures of raw materials (natural aggregates and asphalt binder), machines, material transportation, energy, labor and tax. Due to confidential reasons, the detailed cost for each part could not be separately stated in this paper, while the total cost of asphalt mixture was normalized to one metric ton, which was 191 CHF_{2018}/t for SMA and 194 CHF_{2018}/t for SDA. The transportation of asphalt mixture from the plant to the paving site was performed using a payload of 25 metric tons, where each lorry had a cost of 200 – 240 CHF_{2018} per hour. The driving time was one hour on average plus the unloading time of 15 – 45 min. The combined cost of construction and demolition was between 12 and 32 CHF_{2018} per m^2 of pavement surface, including the expenditures of energy, machine, labor and tax. RAP was transported from the working site to the mixing plant by the same type of lorry. The driving time was one hour without unloading time.

3.2. External cost

The external cost in this paper indicated the monetarization of environmental impacts from LCA. Since the energy cost was regarded as a part of the direct cost, the monetarization focused on greenhouse gases (GHG) emissions and noise impacts. For the GHG cost, the Swiss Federal Office for Spatial Development (ARE, 2021) estimated an average value of 132.8 CHF_{2018} per metric ton of CO_2-eq. This was based on the assumption that the worldwide climate should not warm up more than 2 °C on average above the level before industrialization, so that the negative effects of GHG would not be catastrophic. Hence, the 132.8 CHF_{2018} implied the global cost to avoid one metric ton of CO_2-eq if the 2 °C limit was to be met.

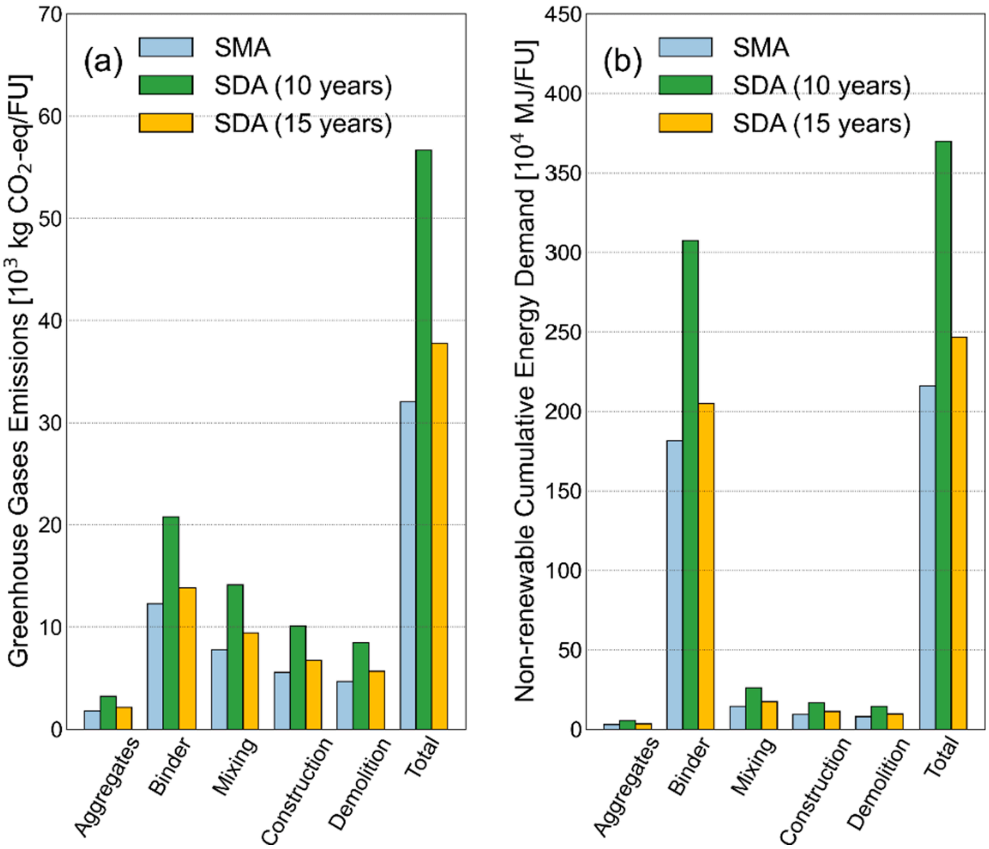

Fig. 4. Greenhouse gases (GHG) emissions (a) and non-renewable cumulative demand (CED) (b) of the three scenarios.

The monetarization of noise impacts was related to the health cost due to road traffic noise. Recent governmental reports (ARE, 2021; FOEN, 2022) showed that the health cost of traffic noise in Switzerland were 1568 million CHF_{2018} in 2018, with 80 % attributed to road traffic. In addition, the Swiss Federal Office for the Environment (FOEN) quantified the health impacts of the yearly traffic noise in Switzerland, presenting results that road traffic noise led to 53 318 DALY/year for the whole country (FOEN, 2019). Herein, we assumed that the health cost was proportional to the DALY of road traffic noise, as described in Eq. (13). $K_{SMA/SDA,X}$ [CHF_{2018}] is the health cost of noise from a local pavement (SMA or SDA) in the service year X, including cost of medical treatment, production loss and reduction in life quality (FOEN, 2022). $HI_{SMA/SDA,X}$ [DALY] is the health impact of traffic noise from the local pavement in the service year X. When $HI_{SMA/SDA,X}$ [DALY] is determined by Eq. (10), Eq. (11) or Eq. (12), it is possible to calculate $K_{SMA/SDA,X}$ [CHF_{2018}] for all the three scenarios.

$$K_{SMA/SDA,X} = \frac{1568 \times 10^6 \times 0.8[CHF_{2018}/year]}{53318[DALY/year]} \bullet HI_{SMA/SDA,X} \tag{13}$$

4. Results

This section presents the results of environmental analysis and monetarization, comprising the GHG emissions and non-renewable CED from the conventional LCA, the noise impacts from the modified LCA, and the monetarization of climate change and human health impacts.

4.1. Greenhouse gases (GHG) emissions and non-renewable cumulative energy demand (CED)

As shown in Fig. 4a, the GHG emissions of SDA with 10 service years were 77 % higher than SMA. This can be explained by the short service life of SDA (10 years) compared to SMA (20 years). When the service life of SDA was extended to 15 years, as indicated by the yellow bar of Fig. 4a, the GHG emissions of SDA would have a sharp reduction by 60 %. The production of binder was the major source of GHG emissions, followed by asphalt mixing, construction and demolition. Although the natural aggregates comprise the largest amount in the asphalt mixture, their impacts on climate change were quite low.

The short service life of SDA also showed drawbacks in non-renewable CED, as shown in Fig. 4b. The scenarios of SMA (20 years) and SDA (15 years) can save non-renewable CED by 71 % and 57 %, respectively, compared to SDA with 10 service years. In addition, more than 80 % of the non-renewable CED was caused by the production of binder, indicating the critical role of asphalt binder in the energy demand for pavement production. Similar result can be found in another study (Farina et al., 2017). Hence, the reduction of virgin binder would be of great importance for a pavement in order to cut down the energy demand.

In summary, Fig. 4 reveals disadvantages of low-noise SDA compared to SMA from the point of view of conventional LCA. The results of SDA with 15 service years showed that an extension of an additional 5 service years can significantly offset the weakness of SDA in GHG emissions and non-renewable CED. However, the low-noise benefit of SDA cannot be reflected by traditional LCA, which should be modified for a comprehensive evaluation.

4.2. Human health impacts

The human health impacts were calculated by the ReCiPe endpoint method for raw material production, asphalt mixing,

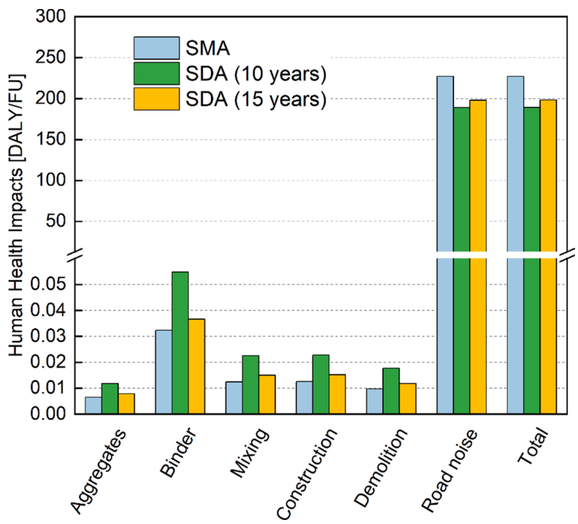

Fig. 5. Human health impacts of the three scenarios.

construction and demolition, and by Eq. 10–12 for road traffic noise. The results in disability adjusted life years (DALY) are shown in Fig. 5. It can be seen that more than 99.9 % of the total DALY was caused by road traffic noise, indicating that the human health impacts of raw material production, asphalt mixing, construction and demolition can nearly be ignored compared to noise. Overall, compared to the reference SMA, the scenarios of SDA (10 years) and SDA (15 years) reduced the DALY by 17 % and 13 %, respectively. Therefore, in the life cycle of a pavement surface, the road traffic noise plays a dominated role in human health, which can be effectively improved by using SDA.

4.3. Monetarization

Section 4.1 and Section 4.2 present both the weakness of SDA in GHG emissions and CED, and the strength of SDA in human health. These trade-offs can be further integrated by converting the environmental indicators into monetary units. Table 2 shows the results of monetarization based on the FU. The asphalt mixture referred to the cost of raw materials, machines, energy demand, material transportations, labor and tax. The road construction and demolition (C&D) included the transportation of asphalt mixture and on-site work and transportation of RAP. For the minimum C&D cost, we considered the lorry with 200 CHF_{2018}/(hour*lorry), the driving time of one hour from the plant to site, the unloading time of 15 min, the on-site work with 12 CHF_{2018} per m^2 of pavement surface, and the driving time of one hour from the working site to the plant. The maximum C&D cost considered the lorry with 240 CHF_{2018}/(hour*lorry), the driving time of one hour from the plant to the working site, the unloading time of 45 min, the on-site work with 32 CHF_{2018} per m^2 of pavement surface, and the driving time of one hour from the working site back to the plant.

The monetarization of GHG emissions was dependent on cost of 132.8 CHF_{2018} per metric ton of CO_2-eq (Section 3.2) and the quantity of GHG in Fig. 4. The health cost considered the results in Fig. 5 and the assumption in Eq. (13). According to Table 2, the health cost due to noise was around 9 times the cost of pavement production (asphalt mixtures and C&D), presenting great impacts of road traffic noise from the monetary point of view. The GHG cost was comparable to the cost of material transportation. Compared to SMA, the SDA reduced the total cost by 10 % – 17 %. Moreover, the two SDA scenarios (with 10 and 15 service years) presented comparable total cost, with lower minimum cost in SDA (10 years) and lower maximum cost in SDA (15 years).

5. Discussion

This section discusses the factors relating to the uncertainty of this LCA. As indicated in Section 2.2.4, the inventory analysis of road traffic noise assumed constant vehicle speed and climate condition. This paper excluded the effects of acceleration or deceleration of vehicles, together with rainy and snowy conditions. These are complex factors which have seldom been studied in the acoustical analysis of road traffic (Can and Aumond, 2018; Fiedler and Zannin, 2015), thus it is challenging to quantify them in LCA using current models. Apart from the acoustical parameters, the effects of pavement surface characteristics, such as roughness, were also not considered in this paper. The difference in roughness between SMA and SDA, and the changing roughness of pavement surface over the service years, can both lead to different fuel consumptions of vehicles (Noshadravan et al., 2013), which can be reflected in the LCA results. A potential solution is to measure the roughness of pavement surface in the field (such as the international roughness index, IRI) and estimate the extra fuel consumption by modeling (Santos et al., 2017). In addition, the work zone management and its effect on fuel consumption during the construction and demolition was not differentiated in this LCA. The reasons were on the one hand, the unavailability of data from the field, and on the other hand, the detouring possibilities of the nearby roads (Fig. 3). For the evaluation of noise impacts, this paper assumed that high annoyance and high sleep disturbance would not result in “years of life lost”, but only incur the “years lived with disability”. This excluded the possible death of inhabitants as a secondary cause of noise disturbance during the temporal scope of LCA.

The monetarization in Section 4.3 can be seen as an extension of LCA, corresponding to the FU, processes and environmental indicators. However, this paper quantified the health cost only based on the noise impacts, disregarding the health cost due to other environmental burdens such as the particle matter (PM) during the use phase of pavements. This is because on the one hand, the fuel consumptions of vehicles during the use phase that generates great amounts of PM were not included in this LCA. On the other hand, the health impacts due to PM from other processes (raw material productions, mixing, construction and demolition) can nearly be neglected compared to the DALY of noise (Fig. 5). Additionally, the external cost of noise is not limited to human health. For example, the Zurich Kantonal Bank in Switzerland has demonstrated that the road traffic noise can lead to the loss of value in real estates, such as rent and house prices (ZKB, 2012; ZKB and FOEN, 2011). This value loss was quantified based on the willingness of people to pay for a

Table 2
Monetarization of the three scenarios for the service life of 30 years (in 10^3 CHF_{2018}/FU with 1 CHF_{2018} = 1.02 USD_{2018}).

	Category	SMA	SDA (10 years)	SDA (15 years)
Direct financial cost	Asphalt mixture	107	197	131
	Construction and demolition	108 – 270	215 – 538	143 – 358
	Transporting asphalt mix	*6 – 9*	*10 – 17*	*7 – 11*
	Working on-site	*98 – 256*	*197 – 511*	*131 – 341*
	Transporting RAP	*4 – 5*	*8 – 10*	*5 – 6*
External cost	GHG emissions	4	8	5
	Health cost due to road traffic noise	5341	4445	4659
Total		5560 – 5722	4865 – 5188	4938 – 5153

quiet environment when the sound level was higher than 50 dB at daytime and 40 dB at night. Therefore, in future research, we suggest to not only quantify the number of buildings and people around the road test section, but also clarify the living area of each building. Then it is possible to estimate the house price and rent of the affected buildings, which can be further used to calculate the value loss due to road traffic noise.

6. Conclusion

This paper presents modified of life cycle assessment for low-noise urban roads, including the inventory of road traffic noise from acoustical monitoring and monetarization. The modified method was applied in a road test section in Switzerland, with conclusions drawn as follows:

(1) For the test section, compared to SMA, SDA with 10 service years led to additional greenhouse gases emissions and non-renewable cumulative energy demand by more than 70 %. If SDA can be replaced every 15 years, the GHG and CED can be significantly lowered.
(2) For the test section, the health impacts (in DALY) of pavement production (materials, mixing, construction and demolition) are negligibly small compared to the health impacts due to road traffic noise. In total, the SDA with 10 and 15 service years presented reduced DALY by 17 % and 13 %, respectively, in comparison to SMA.
(3) For the test section, the health cost due to road traffic noise was around 9 times the cost due to pavement production. The total costs (production, GHG emission and health impact) of SDA with 10 and 15 service years were comparable. Both were 10 %–17 % lower than the cost of SMA.

In future research, we suggest to include more factors such as complex climate conditions and acceleration/deceleration of vehicles, in order to improve the accuracy of noise prediction. Moreover, the value loss of real estate due to road traffic noise should also be considered in the monetarization.

CRediT authorship contribution statement

Zhengyin Piao: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Writing – original draft. **Urs Waldner:** Supervision, Investigation, Software, Validation, Writing – review & editing. **Kurt Heutschi:** Conceptualization, Supervision, Funding acquisition, Project administration, Investigation, Software, Validation, Writing – review & editing. **Lily D. Poulikakos:** Conceptualization, Supervision, Funding acquisition, Project administration, Investigation, Validation, Writing – review & editing. **Stefanie Hellweg:** Conceptualization, Supervision, Funding acquisition, Project administration, Investigation, Methodology, Validation, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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