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Life Cycle Assessment of Representative Swiss Road Pavements for National Roads with an Accompanying Life Cycle Cost Analysis

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ABSTRACT. The subject of this paper is an environmental Life Cycle Assessment (LCA) and Life Cycle Cost Analysis (LCCA) of processes needed to construct and maintain representative Swiss asphalt, concrete and composite pavements (including subbase layers) applicable for the Swiss national road network over a period of 75 years. The environmental indicators analyzed are the Global Warming Potential indicator, the non-renewable Cumulative Energy Demand and the Swiss Ecological Scarcity indicator. Processes of the use phase of the road (fuel consumption, noise, etc.) have been evaluated qualitatively based on intensive research. The study shows that the Global Warming Potential of concrete and asphalt pavements equilibrates over the analysis period and that concrete pavements compared to asphalt and composite pavements offer advantages in regards to the non-renewable

Cumulative Energy Demand, the Ecological Scarcity Indicator and Life Cycle Costs. The qualitative evaluation of the processes of the use phase shows for example the positive qualities of concrete pavements regarding fuel consumption and permanent noise properties.

INTRODUCTION. The road infrastructure sector aims to contribute its part to sustainable development by reducing the environmental pollution stemming from the road network and all processes and services associated with it. Therefore, several studies analyzing the environmental impacts of pavement constructions and their materials have been carried out in the first decade of this millennium [1-10].

This study analyzes all processes needed to construct and maintain typical Swiss asphalt, concrete and composite road pavements (including subbase layers) for national roads (highways) over a time span of 75 years by performing Life Cycle Assessments (LCAs) combined with Life Cycle Cost Analyses (LCCAs). Thereby, also different maintenance strategies and their influence on the environmental and economic results will be studied.

The three environmental indicators to demonstrate the environmental performance of the road pavements are the IPCC Global Warming Potential indicator (GWP) [11], the non-renewable Cumulative Energy Demand (n-r CED) [12] and the Swiss Ecological Scarcity indicator 2006 (EcoScar) [13]. These three indicators are used frequently for political decision-making processes in Switzerland.

The cost values for the LCCA were based on the Cost Analysis 2011 of the Swiss Builders Association and were adapted and confirmed by national and international expert opinions.

Since the research project was limited to a specific time frame, the study focused on the analysis of all processes needed to construct and maintain the road pavements including deconstruction processes. Processes of the use phase of the road (fuel consumption, noise, etc.) have been evaluated only qualitatively based on an intensive literature research to give a rough outlook, how the use phase could influence the LCA and LCCA results. All processes analyzed quantitatively within this study can be seen in **Table 1**.

Table 1. Analyzed Processes

New Construction processes	**Maintenance processes**
Material Production	Pavement/ Layer Deconstruction
Material Transportation	Transportation of Deconstructed Material
Pavement Construction	Recycling of Deconstructed Materials
	Material Production
	Material Transportation
	Pavement/ Layer Construction

METHODOLOGIES. The Life Cycle Assessment (LCA) [14] and Life Cycle Cost Analysis (LCCA) [15] methodologies observe and analyze a product or service over its entire life cycle in order to determine its environmental (LCA) and economic impacts (LCCA). At the Pavement Life Cycle Assessment Workshop carried out by the University of California Pavement Research Center in 2010, the participating international experts set up a framework for pavement LCAs [16] which was used as the basis for the pavement LCA of this study. The LCA and the LCCA studies were carried out in the following steps.

- Definition of the scope of the study according to the aspired goals
  - Definition of road pavements to be analyzed (functional unit - physical dimensions, performance requirements)
  - Identification of processes occurring in life cycle phases analyzed (**Table 1**)
  - Definition of analysis period
  - Definition of maintenance strategies
- Quantification of inputs and outputs (energy, materials, emissions, etc.) for all analyzed new construction and maintenance (Life Cycle Inventory Analysis – LCI)
- Weighting and assessment of determined inputs and outputs according to the selected

environmental indicators (Life Cycle Impact Assessment – LCIA)

- Quantification of costs for all analyzed new construction and maintenance processes
- Discussion and interpretation of determined results

SCOPE. The functional unit is a measure for the performance of the analyzed product system and is a reference to which all inputs and outputs relate. For road pavements, the physical dimension and the pavement performance describe the functional unit [16]. For the analysis of Swiss national roads (highways), the functional unit was defined as a pavement construction with the width of 20.5 m (4 lanes) and a length of 10 km (physical dimension) [17] and a pavement construction of the traffic load class T6 (pavement performance - daily equivalent traffic load > 3 000 … 10 000 average daily passages of equivalent single axle load on one lane during a significant period under observation) [18]. Subgrades, embankments, drainages, shoulders, crash rails, road marking, etc. are not included in the analysis.

Table 2 shows all road pavements investigated and the layers and materials used in each. These road pavements can be seen as typical for the Swiss national road network [18, 19].

Table 2. Road pavements

	Asphalt	**Concrete**	**Composite**
Wearing Course	30 mm AC 8 H or 30 mm AC MR 8 ASTRA	50 mm Exposed aggregate concrete	30 mm AC 8 H or 30 mm AC MR 8 ASTRA
Base course or concrete layer	70 mm AC B 22 H or 80 mm AC EME 22 C1	190 mm Bottom concrete	240 mm Bottom concrete
Road base	80 mm AC T 22 H or 80 mm AC EME 22 C2	80 mm AC T 22 N or 100 mm AC F 22	80 mm AC T 22 N or 100 mm AC F 22
Subbase			
Variant 1	110 mm AC F 22 and 200 mm Round gravel (or 160 mm Crushed gravel)	150 mm Hydr. stab. subbase	150 mm Hydr. stab. subbase
Variant 2	160 mm AC F 22	150 mm Round gravel (or 120 mm Crushed gravel)	150 mm Round gravel (or 120 mm Crushed gravel)
Variant 3	132 mm Bitum. stab. subbase *and* 200 mm Round gravel (or 160 mm Crushed gravel)		
Variant 4	192 mm Bitum. stab. subbase		
Variant 5	160 mm Hydr. stab. subbase *and* 150 mm Round gravel (or 120 mm Crushed gravel)		
Variant 6	160 mm Hydr. stab. subbase		

AC … Asphalt concrete; 8, 22 … Upper face value of the biggest used mineral aggregate [mm]; MR … rough textured wearing course
B … Base course; T … Road base; F … Subbase; EME … High-modulus asphalt; C1 … Very high resistance against deformation;
C2 … Excellent resistance against deformation; N … Mixture type for normal loads; H … Mixture Type for High Loads;
Hydr. stab. … Hydraulically stabilized; Bitum. stab. … Bituminous stabilized; ASTRA … Federal road office (Bundesamt für Strassen);

Average lifetimes, i.e. the period which can be identified as the life cycle of the different road constructions, are difficult to determine, due to the fact that road infrastructure is maintained frequently to ensure an adequate level of service. Therefore, the road pavements are analyzed over a chosen analysis period, which for this study was set to 75 years. The length of the analysis period was chosen to be 1.5 times the average lifetime of a subbase layer (50 years) [16]. The selected length of the period allows the reader to follow and understand the progression of the determined environmental and economic results.

The life cycle phases of the road pavements, i.e. material production, pavement construction, use phase, pavement deconstruction, recycling and waste treatment, occur depending on the length of the analysis period and the associated maintenance strategy. As mentioned before, processes of the use phase of the road (fuel consumption, noise, etc.) have only been evaluated qualitatively based on an intensive research. The maintenance strategies analyzed were compiled based on national and international experiences and expert opinions, and can be seen as exemplary. Thereby, the minimum (variant 1), the maximum (variant 2) and the aspired lifetimes (variant 3) of the different pavement layers were identified, and based on these lifetimes, the three comparable maintenance strategies for each pavement type were compiled (**Table 3**).

Table 3. Analyzed maintenance strategies

Variant1 1- minimum lifetimes

Asphalt		**Concrete**		**Composite**	
Replacement of	*after*	*Replacement of*	*after*	*Replacement of*	*after*
Wearing course	**7.5 Years**			**Wearing course**	**7.5 Years**
Wearing and base course	**15 Years**			**Wearing course**	**15 Years**
Wearing course	**22.5 Years**			**Wearing course**	**22.5 Years**
Wearing and base course	**30 Years**	**Exposed aggregate and bottom concrete**	**30 Years**	**Wearing course and bottom concrete**	**30 Years**
Wearing course	**37.5 Years**			**Wearing course**	**37.5 Years**
Total replacement	**45 Years**			**Wearing course**	**45 Years**
Wearing course	**52.5 Years**			**Wearing course**	**52.5 Years**
Wearing and base course	**60 Years**	**Total replacement**	**60 Years**	**Total replacement**	**60 Years**
Wearing course	**67.5 Years**			**Wearing course**	**67.5 Years**
Wearing and base course	**75 Years**			**Wearing course**	**75 Years**

Variant 2 – maximum lifetimes

Asphalt		**Concrete**		**Composite**	
Replacement of	*after*	*Replacement of*	*after*	*Replacement of*	*after*
Wearing course	**10 Years**			**Wearing course**	**10 Years**
Wearing and base course	**20 Years**			**Wearing course**	**20 Years**
Wearing course	**30 Years**			**Wearing course**	**30 Years**
Wearing and base course	**40 Years**	**Total replacement**	**40 Years**	**Total replacement**	**40 Years**
Total replacement	**50 Years**			**Wearing course**	**50 Years**
Wearing course	**60 Years**			**Wearing course**	**60 Years**
Wearing and base course	**70 Years**			**Wearing course**	**70 Years**

Variant 3 – aspired lifetimes

Asphalt		**Concrete**		**Composite**	
Replacement of	*after*	*Replacement of*	*after*	*Replacement of*	*after*
Wearing course	**12.5 Years**			**Wearing course**	**12.5 Years**
Wearing and base course	**25 Years**			**Wearing course**	**25 Years**
Wearing course	**37.5 Years**			**Wearing course**	**37.5 Years**
Total replacement	**50 Years**	**Total replacement**	**50 Years**	**Total replacement**	**50 Years**
Wearing course	**62.5 Years**			**Wearing course**	**62.5 Years**
Wearing and base course	**75 Years**			**Wearing course**	**75 Years**

Total replacement … replacement of all pavement layers including subbase

LIFE CYCLE INVENTORY ANALYSIS (LCI). LCI quantifies all relevant inputs and output of the analyzed processes, e.g. materials and fuels applied as well as emissions and waste products. The inputs and outputs for this study are based on data surveys conducted in cooperation with different partners of the Swiss road infrastructure sector, and on the ecoinvent database, a Swiss LCI-database provided by the Swiss Federal Institute of Technology (ETH) and its associated scientific environment [20].

In previous publications, the LCI and the LCA of the different life cycle phases were compiled and analyzed in great detail. The material production processes were analyzed in Gschösser *et al.* [21, 22]. Pavement construction, pavement deconstruction, recycling processes and material transport were investigated in Gschösser *et al.* [23]. All inputs and outputs for all modeled processes and all LCI-related data can be found in the **Supporting Information** (Table S 1 – S 21).

Table 4 shows the production and recycling options studied for the different materials.

Table 4. Material production properties

	Layer	*Asphalt/ Cement type*	*Production options*	*Recycling options*
Asphalt	*Wearing course*	AC 8 H AC MR 8 ASTRA	**Standard production** Thermal energy: 305 MJ/t Moisture of mineral aggregates: 4% Heated to 180°C; **Optimized production** Thermal energy: 176 MJ/t Moisture of mineral aggregates: 2% Heated to 115°C	No recycling
	Base course	AC B 22 H AC EME 22 C1	**Standard production** **Optimized production**	No recycling Average recycling Maximum recycling
	Road base	AC T 22 N AC T 22 H AC EME 22 C2	**Standard production** **Optimized production**	No recycling Average recycling Maximum recycling
Concrete	*Exposed aggregate concrete*	CEM I CEM II / A-LL CEM II / B-T CEM III / A	**Standard clinker and cement production** Thermal energy: 3450 MJ/ t clinker Thermal substitution rate of waste: 46.5 %	No recycling
	Bottom concrete	CEM I CEM II / A-LL CEM II / B-T CEM III / A [24]	**Standard clinker and cement production**	No recycling 25% Concrete aggregates 50% Concrete aggregates 75% Concrete aggregates 100% Concrete aggregates
Subbase	*Asphalt subbase*	AC F 22	**Standard production** **Optimized production**	No recycling Average recycling Maximum recycling
	Cold-bound Subbase	Bituminous stabilized Hydraulically stabilized	**At plant** **In-situ**	No recycling 100% Recycling
	Unbound subbase	Round gravel Crushed gravel	**At plant**	No recycling 100% Recycling

CEM I … Portland cement; CEM II / A-LL … Portland limestone cement; CEM II / B-T … Portland shale cement

CEM III / A … Blast furnace cement

For the transport of construction materials from plant to building site and for the transport of deconstructed material from building site to recycling plant or storage, an average transport distance of 25 km was defined based on empirical data from the expert panel supporting this project.

To determine the LCI data for construction and deconstruction, the exact processes and the necessary road construction equipment have been modeled in detail in cooperation with leading Swiss construction companies.

Regarding material recycling, it was assumed that all construction materials can be recycled to reusable materials (concrete granulates, asphalt granulates, etc.) after deconstruction. Concerning the allocation of recycling processes between deconstruction and the production of new materials it was defined that the transport from the storage of reusable materials ("recycling pool") is the first process to be included into material production processes. All recycling processes and transport processes to the recycling plant and the “recycling pool” are assigned to the deconstructed layer.

COSTS FOR NEW CONSTRUCTION AND MAINTENANCE. Cost values are generally based on the Cost Analysis 2011 of the Swiss Builders Association [25] and were adapted and confirmed by the aforementioned expert panel.

In Switzerland, no national roads with concrete or composite pavements have been built over the past two decades. Therefore, no current market values for these two pavement types could be used for the LCCA. In an additional study representative cost values from Germany and Austria were collected, where concrete and composite pavements are applied frequently for national roads (highways). Thereby the ratio between the costs for asphalt and concrete pavements (without subbase layer) was determined. The cost values for Switzerland were adjusted according to this ratio from Germany and Austria, in order to obtain "market-oriented" cost values for layers of concrete and composite pavements in Switzerland.

For the existing Swiss cost data, a ratio of 1: 2.1 (asphalt to concrete) was given. In Germany, the ratio was 1: 1.60 (asphalt to concrete) and in Austria, 1: 1.46, resulting in an average ratio of 1: 1.53. Swiss cost values for concrete layers were then adjusted in order to obtain a ratio of 1: 1.53 between costs for asphalt and concrete pavements (without foundation layer).

The life cycle cost calculation was then carried out after consultation with the Advisory Group with a discount rate of 2%.

The cost values could not be split up for each individual life cycle phase because of the current unavailability of disaggregated data from construction companies in Switzerland. The cost values given are combined for new construction processes of pavement layers (material production, material transport to building site and layer construction) and all deconstruction processes (deconstruction of layer, transport of reclaimed material to recycling plant).

LIFE CYCLE IMPACT ASSESSMENT (LCIA). LCIA associates Life Cycle Inventory data with specific environmental impact categories and category indicators.

The following environmental indicators were used in the study:

- IPCC Global Warming Potential 2007 (GWP) [kg CO_2-eq] [11]
- Non-renewable Cumulative Energy Demand (n-r CED) [MJ-eq] [12]
- Ecological Scarcity 2006 (EcoScar) [EIP - Environmental Impact Points] [13]

The environmental results of this research were developed gradually. Regarding the first step of the analysis, the life cycle assessment of the production of one cubic meter of road material, it can be seen that the production of asphalt generally has advantages in terms of global warming potential, whereas the production of concrete has lower impacts regarding the non-renewable Cumulative Energy Demand. Furthermore, it can be deduced that recycling does not always have a positive impact on all environmental indicators. For example, the use of concrete granulates for the production of concrete requires higher cement content within the concrete mixture resulting in a higher Global Warming Potential. However, primary resources are saved, which is reflected as a positive effect regarding the Ecological Scarcity indicator [21].

According to the frequency of application and the current state of material production (standard production) for each pavement type, a “standard pavement” was defined in cooperation with experts of the Swiss road infrastructure sector. For these “standard pavements”, the environmental impacts of all material production processes per square meter of road pavement were determined. In parallel, the "best case" pavements for the three different types of pavements were identified (**Table 5**).

Table 5. Results material production per square meter of road pavement

Asphalt

Standard pavement				*„Best Case“ Global Warming Potential and Ecological Scarcity*				*„Best Case“ non-renewable Cumulative Energy Demand*			
[mm]	*Material*	*Recycling*	*Production*	*[mm]*	*Material*	*Recycling*	*Production*	*[mm]*	*Material*	*Recycling*	*Production*
30	AC 8 H	No	Standard	30	AC MR 8 ASTRA	No	Optimized	30	AC MR 8 ASTRA	No	Optimized
70	AC B 22 H	Average	Standard	70	AC B 22 H	Max.	Optimized	70	AC B 22 H	Max.	Optimized
80	AC T 22 H	Average	Standard	80	AC T 22 H	Max.	Optimized	80	AC T 22 H	Max.	Optimized
192	bitum. stab. SB	No	In-situ	110	AC F 22	Max.	Optimized	110	hydr. stab. SB	Max.	Optimized
				160	Recycling granulate	Max.	At plant	160	Recycling granulate	Max.	At plant

kg CO_2-eq/m^2	*MJ-eq/m^2*	*1’000 EIP/m^2*	*kg CO_2-eq/m^2*	*MJ-eq/m^2*	*1’000 EIP/m^2*	*kg CO_2-eq/m^2*	*MJ-eq/m^2*	*1’000 EIP/m^2*
42	**2004**	**62**	**28**	**880**	**32**	**30**	**809**	**40**

Concrete

Standard pavement				**„Best Case“ Global Warming Potential**				**„Best Case“ non-renewable Cumulative Energy Demand and Ecological Scarcity**			
[mm]	*Material*	*Recycling*	*Production*	*[mm]*	*Material*	*Recycling*	*Production*	*[mm]*	*Material*	*Recycling*	*Production*
50	CEM II / B-T	No	Standard	50	CEM III/ A	No	Standard	50	CEM III/ A	No	Standard
190	CEM II / B-T	100 %	Standard	190	CEM III/ A	No	Standard	190	CEM III/ A	100 %	Standard
80	AC T 22 N	Average	Standard	80	AC T 22 N	Max.	Optimized	80	AC T 22 N	Max.	Optimized
120	Crushed gravel	No	At plant	120	Recycling granulate	Max.	At plant	120	Recycling granulate	Max.	At plant

kg CO_2-eq/m^2	*MJ-eq/m^2*	*1’000 EIP/m^2*	*kg CO_2-eq/m^2*	*MJ-eq/m^2*	*1’000 EIP/m^2*	*kg CO_2-eq/m^2*	*MJ-eq/m^2*	*1’000 EIP/m^2*
77	**931**	**64**	**61**	**609**	**58**	**63**	**608**	**48**

Composite

Standard pavement				**„Best Case“ Global Warming Potential and Ecological Scarcity**				**„Best Case“ non-renewable Cumulative Energy Demand and Ecological Scarcity**			
[mm]	*Material*	*Recycling*	*Production*	*[mm]*	*Material*	*Recycling*	*Production*	*[mm]*	*Material*	*Recycling*	*Production*
30	AC 8 H	No	Standard	30	AC MR 8 ASTRA	No	Optimized	30	AC MR 8 ASTRA	No	Optimized
240	CEM II / B-T	100 %	Standard	240	CEM III/ A	No	Standard	240	CEM III/ A	100 %	Standard
80	AC T 22 N	Average	Standard	80	AC T 22 N	Max.	Optimized	80	AC T 22 N	Max.	Optimized
120	Crushed gravel	No	At plant	120	Recycling granulate	Max.	At plant	120	Recycling granulate	Max.	At plant

kg CO_2-eq/m^2	*MJ-eq/m^2*	*1’000 EIP/m^2*	*kg CO_2-eq/m^2*	*MJ-eq/m^2*	*1’000 EIP/m^2*	*kg CO_2-eq/m^2*	*MJ-eq/m^2*	*1’000 EIP/m^2*
96	**1404**	**93**	**79**	**1083**	**89**	**82**	**1081**	**76**

The comparison of the “standard” and "best case" pavements shows that material production processes for asphalt pavements offer larger reduction potentials (with regard to all indicators) than for those for concrete and composite pavements. This can be explained by the higher cement content for recycling concrete and the relatively low potential of the application of CEM III / A (35 – 64 % clinker content and substitution material with long transport distances – from abroad) instead of CEM II / B-T (65 – 79 % clinker content and substitution material with short transport distance).

The analysis of all new construction and maintenance processes demonstrated that (for all three pavement types and all three environmental indicators) material production processes have the greatest influence on the environmental results both for new construction (about 93%) and maintenance (about 83% for a total replacement).

In the last step of the LCA, the standard pavements were analyzed over the analysis period of 75 years. This analysis period takes into account all material production, material transport, pavement construction, layer deconstruction and layer reconstruction processes occurring due to the selected maintenance strategy. The three standard pavements were compared for the same maintenance strategy (variant 1, 2 or 3). The reference value for the normalization of the results was the result for standard asphalt pavement after 75 years and the application of maintenance strategy variant 1 (100 %). In the main paper, only the results for maintenance strategy 1 will be compared due to the limited extent of the paper. The results for the maintenance strategies 2 and 3 can be found in the **Supporting Information** (Figure S 1 – S 8). The comparison of the results of the three pavement types for these two maintenance strategies showed that the relation between the pavement types is nearly identical to the relation determined for maintenance variant 1.

Figure 1 shows that the Global Warming Potential of the asphalt and the concrete pavement frequently equilibrate over the period analyzed. ***Figure 2*** and ***Figure 3*** demonstrate that the concrete pavement contains significant advantages regarding the non-renewable Cumulative Energy Demand and the Ecological Scarcity indicator in comparison to the asphalt and the composite pavement. These results can be explained by the feedstock energy related to the large amount of bitumen within the asphalt mixture and the great influence of longer lifetimes.

Figure 1: Normalized progression of GWP results

Figure 2: Normalized progression of non-renewable CED results

Figure 3: Normalized progression of Ecological Scarcity results

The analysis of the maintenance variants with longer lifetimes (version 2 and version 3) showed, compared to the results for maintenance variant 1, for all three pavement types a big reduction potential regarding all three environmental indicators (e.g. asphalt variant 3 to variant 1: -25 % GWP). As mentioned before, the comparison of the results of the three pavement types for the maintenance strategies 2 and 3 demonstrated a nearly identical relation between the pavement types as for maintenance variant 1 (**Supporting Information** Figure S 1 – S 6).

The substitution of CEM II / B-T by CEM III / A in the individual concrete layers reduces the GWP of the complete concrete pavement by 10% over the whole analysis period. Regarding the n-r CED and the EcoScar indicator the substitution of CEM II / B-T by CEM III / A causes only a minimal reduction of less than 1 % over 75 years.

For the asphalt production, the influence that optimized production characteristics with lower thermal energy needs induced by the use of special bitumen have on the overall results could be investigated. However, according to expert opinions the usage of asphalt mixtures with special bitumen having lower energy requirements will be uncommon in Switzerland in the future; therefore, this alternative is not further considered in the overall analysis.

LIFE CYCLE COST ANALYSIS (LCCA). The comparison of the Life Cycle Costs for the three standard pavement shows that the concrete pavement causes the lowest costs over the analysis period, which can be explained by the long lifetimes of concrete layers. The costs for the asphalt and composite pavement equilibrate over the analysis period.

All three pavement types have approximately the same new construction costs, although the costs of the three upper layers (without the subbase layer) of the asphalt and the concrete pavements have a ratio of 1 : 1.53. The nearly identical total construction costs (including subbase layer) can be explained by the expensive bituminous stabilized subbase of the standard asphalt pavement and the more economic unbound subbase of the standard concrete and composite pavements.

Figure 4: Normalized progression of Life Cycle Costs

The analysis of the maintenance variants with longer lifetimes (version 2 and version 3) showed, compared to the results for maintenance variant 1, for all three pavement types a big reduction potential for the Life Cycle Costs (e.g. concrete variant 3 to variant 1: -20 % Life Cycle Costs). As mentioned before, the comparison of the results of the three pavement types for the maintenance strategies 2 and 3 demonstrated a nearly identical relation between the pavement types as for maintenance variant 1 (**Supporting Information** Figure S 7 – S 8).

PROCESSES OF THE USE PHASE. In recent years, different studies showed the advantages of rigid concrete pavements compared to viscoelastic asphalt pavements regarding rolling resistance and associated fuel consumption (1 to 6% less for freight transport) [5, 26, 27]. These studies also demonstrated the great influence of the fuel consumption on the environmental results, which can be up to hundred times higher for vehicle operation in comparison to all construction and maintenance processes [9].

Concerning noise-reducing wearing courses for asphalt pavements, porous asphalt or noise-reducing stone mastic asphalt and for concrete pavements, exposed aggregate concrete should be highlighted. As such, wearing courses made of exposed aggregate concrete can keep their noise reduction potential over their lifetime almost constant [28].

Directly after the construction of asphalt pavements the mineral aggregates are covered with a bitumen film resulting in a reduced grip. After removal of the bitumen film, the grip reaches its maximum and then decreases over a period of time until it stays at a certain level [28]. Exposed aggregate concrete surfaces offer good and lasting grip properties. The dense surface of exposed aggregate concrete layers guarantees a short discharge time, and therefore a sufficient grip in wet weather conditions [29].

The transversal planarity has a major impact on traffic safety, because of the transverse orientation of the outflow of surface water [30]. The tendency of asphalt pavements to rutting consequently causes an impairment of road safety [31].

The brightness of concrete pavements in comparison to the dark asphalt roads raises the level of road safety especially at night and in tunnels. Due to the brightness of concrete pavements, a large part on lighting energy can be saved [32].

Regarding traffic load, noise and environmental pollution during the construction and maintenance phases, asphalt pavements are advantageous because they can be opened to traffic two days after the installation. Comparatively, concrete pavements have a waiting period of approximately 12 days [33]. However, for concrete pavements after the new construction of the pavement, no major maintenance interventions are needed for a long period (up to 40 years or more). As for asphalt pavements, within relatively short intervals, layers need to be replaced. This causes the necessary structural measures and the related additional traffic, noise and environmental burdens.

DISCUSSION. The results and statements of this research indicate that an application of concrete pavements for national roads (highways) in Switzerland could entail certain environmental and economic benefits.

The fact that in Germany and Austria, the ratio between the new construction costs of asphalt and concrete pavements (excluding subbase) is about 1 : 1.5, proves that the cost values for concrete pavements in Switzerland (ratio is about 1: 2) contain uncertainties due to lacking application in the last two decades.

To achieve environmental optimization regarding the analyzed life cycle phases, two aspects having a great influence on the results of the LCA could be pointed out: first, the material production and second, the maintenance strategies.

Concerning the material production, this LCA study quantified the possible reduction potentials (regarding the three environmental indicators used) by comparing standard material production processes and “best practice” production processes. Thereby, for example the best practice material production (per square meter road pavement) with optimized production technology and equipment, optimum recycling content, less energy use and alternative raw materials offers reduction potentials of 33% for the GWP of asphalt pavements, 21% and 18% for the GWP of concrete and composite pavements in comparison to standard material production processes for the different pavement types. Therefore, environmental databases such as ecoinvent need to be updated frequently, so that investments into more environmental friendly production processes lead to better LCI datasets and precise LCA results.

Due to the great influence of maintenance strategies on both the environmental and economic results, the mainly economic-driven pavement management systems should be combined with the LCA methodology in the future. This study showed that concrete pavements offer a longer service life with identic new construction costs as for asphalt and composite pavements but with high initial environmental impacts. However, the longer service life compensates these environmental impacts over the analysis period, which leads to environmental and economic advantages for concrete pavements. Therefore it can be said that for the case of Switzerland the choice of the pavement type, which is connected to a more environmental friendly maintenance strategy, also lowers the life cycle costs.

The literature research regarding the processes of the use phase showed the positive characteristics of concrete pavements concerning rolling resistance (and therefore fuel consumption), long term noise generation characteristics as well as road safety (e.g. grip and transversal planarity). Results stated within the literature suggest that the use phase of the road has a great influence on the outcome of road LCA and LCCA studies (e.g. up to hundred times higher for vehicle operation in comparison to construction and maintenance processes). However, a clear statement on the overall environmental and economic performance of different road pavements can be made, when all important use phase processes could have been investigated more detailed and were included into the system boundaries of road LCA and LCCA studies.

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SUPORTING INFORMATION. The Supporting Information includes data and information with regard to the road pavements analyzed, the LCI data and the results for national and cantonal roads (for the analyses over 25, 50 and 75 years) for all utilized environmental indicators.

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