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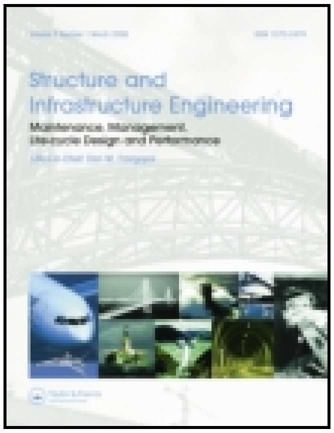

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Environmental analysis of new construction and maintenance processes of road pavements in Switzerland

Florian Gschösser [a], Holger Wallbaum [a] & Bryan T. Adey [a]

[a] Department of Civil, Environmental and Geomatic Engineering, Institute of Construction and Infrastructure Management, ETH Zurich 8093, Zurich

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Environmental analysis of new construction and maintenance processes of road pavements in Switzerland

Florian Gschösser*, Holger Wallbaum and Bryan T. Adey

Department of Civil, Environmental and Geomatic Engineering, Institute of Construction and Infrastructure Management, ETH Zurich 8093, Zurich

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The subject of this paper is an environmental analysis of processes needed to construct (material production, pavement construction, transport) and maintain (pavement deconstruction, recycling, material production, pavement construction, transport) representative Swiss asphalt, concrete and composite pavements (including subbase layers). The analysed environmental indicators are the IPCC Global Warming Potential indicator, the Ecological Scarcity Indicator and the Non-renewable Cumulative Energy Demand indicator. It is shown that material production processes have the largest impact on the values of the analysed indicators, and that pavement construction and deconstruction processes have a marginal impact on the analysed indicators in comparison to material production, transport and recycling processes. It is also demonstrated that the values of the IPCC Global Warming Potential indicator and the Ecological Scarcity indicator for the processes needed to construct and maintain concrete and composite pavements are higher than those for all processes required to construct and maintain asphalt pavements, due to the greater thickness of concrete and composite pavements. The values of the Non-Renewable Cumulative Energy Demand indicator are higher for processes applied to construct and maintain asphalt pavements than for concrete pavements, due to the use of bitumen within asphalt pavements, which causes a depletion of fossil energy resources.

Keywords: roads and highways; pavement design; environment; life cycles; infrastructure

Introduction

Problem

One of the main aims of those pursuing sustainable development is to reduce environmental pollution. In the Kyoto protocol, several countries, communities and economic sectors agreed to reduce their environmental pollution by specific percentages by 2020 in comparison with their environmental pollution in 1990. In recent years, several environmental indicators have been developed to measure the environmental impacts of the different processes related to the life cycles of products.

The road infrastructure sector is a sector of the economic activity that provides services of transport of people and goods by means of a physical road network, and it encompasses technologies, physical elements (e.g. pavements, signs, tunnels, bridges, etc.) and organisations (e.g. national road administration, regulatory institutions, etc.). The road infrastructure sector can contribute to sustainable development by reducing the negative environmental impact of the processes related to its 'product', the road network, over its life cycle.

Over the last decade, several studies analysing pavements regarding their environmental impacts have been carried out. Muench (2010) showed that only two of these studies, one Finnish study (Mroueh, Eskola, Laine-Ylijoki, & Wellman, 2000) and one study carried out in the US (Weiland, 2008), analysed road pavement life cycles in significant detail and broke down environmental impacts to material production, material transport, pavement construction and maintenance. Both studies concentrated on the amount of energy used [MJ] as an environmental indicator, whereas Weiland (2008), also considered CO_2 emissions. The way the indicators were calculated in both of these studies, however, can no longer be considered as up-to-date.

The work presented in this paper is part of one of the first studies in central Europe analysing road pavements (including subbase layers) over their entire life cycle, and which uses the IPCC GWP 2007 indicator [CO_2-eq], which contains all substances that contribute to climate change, and is the indicator on which the Kyoto protocol is based (Solomon *et al.*, 2007). In addition to the IPCC GWP 2007 indicator, the Non-renewable Cumulative Energy Demand

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*Corresponding author. Email: gschoesser@ibi.baug.ethz.ch

[CED, MJ-eq] and the Ecological Scarcity 2006 indicator are used.

The Non-renewable CED [MJ-eq] is an indicator of the direct and indirect consumption of fossil and nuclear energy resources, as well as biomass from primary forests (Boustead & Hancock, 1979; Huijbregts *et al.*, 2010). The Ecological Scarcity 2006 indicator is an environmental indicator, which aggregates and weights the values of a selection of representative environmental impacts determined (Frischknecht, Steiner, & Jungbluth, 2009). These three indicators are often used in Switzerland as the base for discussions and decisions on the sustainability of building and infrastructure projects (KBOB, 2009).

In addition to the determination of the values of representative pavements, the work presented in this paper also highlights the influence of different transport distances for the transportation of the road material from the production plant to the construction site on the values of the sustainability indicators. In order to investigate the reliability of the determined results Monte Carlo Simulations using typical distributions to represent key input parameters were applied.

Goals

In this paper, the impacts regarding the three aforementioned environmental indicators for processes needed for the new construction and maintenance, except for material production processes, which are taken from Gschösser, Wallbaum, and Boesch (2011a, 2011b), are determined for typical asphalt, concrete and composite road pavements (including subbase layers) used in Switzerland for national (highways) and cantonal roads. The specific processes analysed (Table 1) are those related to the new construction of the road pavement and those related to partial or full replacement maintenance interventions.

The influence of the specific processes needed for the new construction and full replacement of the pavements is compared, as well as the influence of different transport distances.

Table 1. Analysed 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

Methodology

The road pavements were analysed using the life cycle assessment (LCA) methodology as described in ISO, EN, and DIN. (2006).

This LCA study is executed in the following steps:

(1) Definition of the scope of the study according to the aspired goal
  Definition of road pavements to be analysed
  Identification of construction processes and machines needed to build layers of analysed pavements
  Identification of deconstruction processes and machines used when layers of pavements are replaced
  Identification of recycling processes needed to upgrade reclaimed material to reusable material and definition of recycling allocation
  Identification of transport processes and vehicles
(2) Quantification of in- and outputs (energy, materials, emissions, etc.) for all analysed processes, i.e. the Life Cycle Inventory Analysis – LCI (ISO *et al.*, 2006)
(3) Weighting and assessment of determined in- and outputs according to the selected environmental indicators, i.e. a Life Cycle Impact Assessment – LCIA ((ISO *et al.*, 2006), including
  Detailed description of environmental indicators
  Results for road pavements of national and cantonal roads
  Demonstration of influence of analysed processes and transport distances
  Uncertainty analysis with Monte Carlo simulation
  Comparison to results of related studies.
(4) Discussion and interpretation of determined results.

Scope of the study

Road pavements

All environmental impacts occurring over the analysed life cycle phases relate to a functional unit (ISO, 2006). The functional unit for pavements of national roads was set as a pavement fulfilling the requirements of the traffic load class T6 (VSS, 1997) with the width of 20.5 m (4 lanes) and a length of 10 km. For cantonal roads the functional unit was defined as a pavement fulfilling the requirements of the traffic load class T5 or T4, 7.5 m (2 lanes) wide and 0.5 km long. All pavement layers in Table 2 are analysed, but subgrades, embankments, drainages, shoulders, crash rails, road marking, etc. are not included in the analyses.

Table 2. Analysed road pavements.

Asphalt pavements			Concrete pavements			Composite PAVEMENTS
T6	T5	T4	T6	T5	T4	T6
Wearing course: 30 mm AC 8 H *or* 30 mm AC MR 8 ASTRA	**Wearing course:** 30 mm AC 8 S *or* 30 mm AC MR 8	**Wearing course:** 30 mm AC 8 S *or* 30 mm AC MR 8	**Wearing course:** 50 mm EA Concrete	**Wearing course:** 50 mm EA Concrete	**Wearing course:** 50 mm EA Concrete	**Wearing course:** 30 mm AC 8 H *or* 30 mm AC MR 8 ASTRA
Base course and road base: 70 mm AC B 22 H 80 mm AC T 22 H *or* 80 mm AC EME 22 C1 80 mm AC EME 22 C2	**Base course and road base::** 60 mm AC B 16 S 60 mm AC T 22 S	**Road base:** 90 mm AC T 22 S	**Concrete layer:** 190 mm bottom concentration	**Concrete layer:** 150 mm bottom concentration	**Concrete layer:** 120 mm bottom concentration	**Concrete layer:** 240 mm bottom concentration
			Interlayer: 80 mm AC T 22 N *or* 100 mm AC F 22	**Interlayer:** 80 mm AC T 22 N *or* 100 mm AC F 22	**Interlayer:** 80 mm AC T 22 N *Or* 100 mm AC F 22	**Interlayer:** 80 mm AC T 22 N *or* 100 mm AC F 22
Subbase: ***S3:*** 110 mm AC F 22 200 mm round gravel *or* 160 mm crushed gravel *or* 160 mm AC F 22 *or* 132 mm BSB 200 mm round gravel *or* 160 mm crushed gravel *or* 192 mm BSB *or* 160 mm hydraulically bound mixture 150 mm round gravel *or* 120 mm crushed gravel *or* 160 mm hydraulically bound mixture	**Subbase:** ***S3:*** 90 mm AC F 32 200 mm round gravel *or* 160 mm crushed gravel *or* 140 mm AC F 32 *or* 108 mm BSB 200 mm round gravel *or* 160 mm crushed gravel *or* 168 mm BSB *or* 160 mm hydraulically bound mixture 150 mm round gravel *or* 120 mm crushed gravel *or* 200 mm hydraulically bound mixture	**Subbase:** ***S3:*** 70 mm AC F 32 200 mm round gravel *or* 160 mm crushed gravel *or* 120 mm AC F 32 *or* 84 mm BSB 200 mm round gravel *or* 160 mm crushed gravel *or* 144 mm BSB *or* 170 mm hydraulically bound mixture	**Subbase:** ***S3:*** 150 mm hydraulically bound mixture *or* 150 mm round gravel *or* 120 mm crushed gravel	**Subbase:** ***S3:*** 150 mm round gravel *or* 120 mm crushed gravel	**Subbase:** ***S3:*** 150 mm round gravel *or* 120 mm crushed gravel	**Subbase:** ***S3:*** 150 mm hydraulically bound mixture *or* 150 mm round gravel *or* 120 mm crushed gravel

(*continued*)

Table 2. (*Continued*).

Asphalt pavements			Concrete pavements			Composite PAVEMENTS
T6	T5	T4	T6	T5	T4	T6
S4: 110 mm AC F 22 *or* 132 mm BSB *or* 160 mm Hydr. Bound Mixture	***S4:*** 90 mm AC F 32 *or* 108 mm BSB *or* 160 mm Hydr. Bound Mixture	***S4:*** 80 mm AC F 32 *or* 96 mm BSB *or* 160 mm Hydr. Bound Mixture	***S4:*** No subbase	***S4:*** No subbase	***S4:*** No subbase	***S4:*** No subbase

Notes: AC, asphalt concrete; 8, 16, 22, 32, Upper face value of the biggest used mineral aggregate; MR, rough textured wearing course; EA, exposed aggregate. B, base course; T, road base; F, Subbase; EME, High-modulus asphalt; C1, very high resistance; C2, excellent resistance; BSB, cold bituminous bound subbase. N, mixture type for normal loads; S, mixture type for strong loads; H, mixture type for high loads.

Table 2 shows the investigated road pavements, including a description of the layers used in each. These road sections are typical for the Swiss national and cantonal road networks (ASTRA, 2007; Canton Aargau, 2008; Canton Zurich, 2008). The thickness of the subbase layers of the analysed pavements depends on the wearing capacity offered by the subgrade on which the road pavement is placed (Table 2). This study analyses road pavements placed on subgrades of the wearing capacity classes S3 and S4 (VSS, 1997).

Construction processes

In this section, the processes required for the construction of the investigated road pavements and their layers are explained. The analyses of construction processes and building machines are based on expert information provided by the two major road construction companies in Switzerland and on data provided by building machine producers.

Asphalt concrete layers

The asphalt concrete pavements consist of an asphalt concrete wearing course, base course and road base (VSS, 2008), which are placed on a subbase layer comprised of diverse materials. Before an asphalt concrete layer is constructed, a bitumen emulsion is sprayed on the subjacent layer, in order to guarantee an optimum adhesive bond. The main construction process, i.e. the paving, of each of these three layers is carried out by utilising an asphalt paver. Thereby, the asphalt paver pushes the transport lorry, which continuously discharges the hot asphalt concrete. The screed of the paver distributes and compacts the discharged asphalt concrete. After the asphalt layer is placed, two rolling processes are executed with a single drum and a compacting process is carried out with a vibration plate to finish the construction process of each asphalt layer. Table 3 shows all processes and machines needed for the construction of an asphalt concrete layer.

Table 3. Processes and building machines utilised for the construction of asphalt layers.

Process	Machine type	Analysed machine
Paving	Asphalt paver	CAT AP 555 E
Rolling	Single drum smooth (vibration compactor)	CAT CS 74 C
Compacting	Vibration Plate	Weber CR 10
Spraying bitumen emulsion	Bitumen sprayer on lorry	Atlas AE 6000

Concrete layers

The concrete pavement analysed consists of 5 m × 5 m unreinforced plates connected by anchors every 50 cm. An exposed aggregate concrete layer is placed atop of the bottom concrete plates. The construction joints between the plates are filled with waterproof joint compounds (Holcim Schweiz AG, 2008). The concrete paving layers are set atop a subbase layer, which can consist of different materials. To avoid material shifting in the subbase layer, an interlayer of asphalt concrete is placed between the concrete paving layers and the subbase (Holcim Schweiz AG, 2008; Werner, 2004).

The construction of the asphalt concrete interlayer requires the same processes and equipment as the construction of an asphalt layer within a pure asphalt pavement (Table 3). The construction of the concrete plates, i.e. the bottom concrete layer, is carried out by slip form pavers, which contribute and compact the concrete over the whole width of the pavement to be constructed. For larger pavement widths, i.e. pavements of the traffic load class T6, the contribution of the concrete is executed by wheel loaders. Modern slip form pavers can also vibrate the anchors into the bottom concrete layer, before the exposed aggregate concrete layer is placed. Directly after the anchors are set, the exposed aggregate concrete layer is constructed with a second slip form paver. This second paver is supplied with concrete by a conveyer belt, which is charged in front of the first paver. Within one day of the top concrete layer being constructed, the joints necessary to compensate for plate movement must be cut. The exposed aggregate surface is achieved by brushing out the cement paste on top, which is possible due to a surface retarder applied after placing the top concrete layer. Before, i.e. together with the retarder, and after the brushing out of the top cement paste, a curing compound is sprayed on the exposed aggregate concrete layer. Table 4 shows all processes and machines applied for the construction of a concrete layer.

Table 4. Processes and building machines utilised for the construction of concrete layers.

Process	Machine type	Analysed machine
Distribution (only for T6)	Wheel loader	CAT 906 H
Paving bottom concrete	Slip form paver	Wirtgen SP 1200
Vibrating anchors	Slip form paver	Wirtgen SP 1200
Paving exposed aggregate concrete	Slip form paver	Wirtgen SP 1200
Spraying retarder and curing compound	Slip form paver	Wirtgen SP 1200
Cutting joints	Joint cutter	Lissmac FS 31 D
Brushing exposed aggregate surface	Wheel loader with brush	CAT 906 H

Composite layers

This study only analyses composite pavements fulfilling T6 traffic load requirements, i.e. pavements for national roads. Composite pavements consist of an asphalt wearing course set atop a continuously reinforced concrete layer. The concrete layer features an increased thickness in comparison to pure concrete pavements. An asphalt concrete interlayer and a subbase support the underlay for the composite layers.

Both the asphalt concrete interlayer and the wearing course are constructed as mentioned earlier. The continuously reinforced concrete layer is constructed with a slip form paver, whereby the reinforcement needs to be placed manually and no joints need to be cut. Table 5 demonstrates all processes and building machines needed for the construction of a composite pavement.

Table 5. Processes and building machines utilised for the construction of composite pavements.

Process	Machine type	Analysed machine
Placing reinforcement	Manually	–
Distribution	Wheel Loader	CAT 906 H
Paving bottom concrete	Slip form paver	Wirtgen SP 1200
Spraying bitumen emulsion	Bitumen sprayer on lorry	Atlas AE 6000
Paving	Asphalt paver	CAT AP 555 E
Rolling	Single drum smooth (vibration compactor)	CAT CS 74 C
Compacting	Vibration plate	Weber CR 10

Subbases

Table 2 shows that national roads, i.e. traffic load class T6, with concrete or composite pavements contain round or crushed gravel or hydraulically stabilised mixtures as subbase materials (VSS, 1997). Subbases for cantonal roads, traffic load class T5 and T4, with concrete pavement consist of either round or crushed gravel. Asphalt pavements for all three traffic load classes can contain either hot or cold mixed asphalt concrete subbases (cold bituminous stabilised mixtures), hydraulically stabilised mixtures as well as crushed or round gravel.

Unbound subbases and hydraulically stabilised subbases centrally mixed. Unbound subbases, i.e. round or crushed gravel, and hydraulically stabilised subbases mixed in a concrete plant or a mobile mixing plant at site are distributed with a bulldozer over the width of the pavement to be constructed. After the subbase material is placed, two rolling processes with a single drum and a compacting process with a vibration plate are executed to finish the construction process of the subbase layer. Table 6 shows all processes and machines necessary for the construction of an unbound or centrally mixed hydraulically stabilised subbase layer.

Hot and cold mixed asphalt concrete subbases. Hot and cold bituminous bound subbase mixtures require the same processes and building machines as the construction of one of the three top asphalt layers (Table 3). Since the asphalt paver limits the maximum thickness of an asphalt layer produced in one operation to 130 mm, for bituminous subbases with a greater thickness all processes need to be repeated according to the overall thickness of the subbase layer.

Hydraulically and cold bituminous stabilised subbases mixed in situ. The in-situ mixing method combines the production with the construction process of the subbase layer. The soil or the former unbound subbase existing on site is mixed with the binder, i.e. cement or bitumen, by a special stabiliser (Wirtgen Group, 2009). Gschösser *et al.* (2011b) analysed the in-situ mixing as a material production process. Therefore, the construction of an in-situ mixed subbase consists of two rolling processes with a single drum and a compacting process carried out with a vibration plate (Table 6).

Table 6. Processes and building machines required for the production of unbound or centrally mixed hydraulically stabilised subbases.

Process	Machine type	Analysed machine
Distribution	Wheel loader	CAT 906 H
Rolling	Single drum smooth (vibration compactor)	CAT CS 74 C
Compacting	Vibration plate	Weber CR 10
Spraying bitumen emulsion	Bitumen sprayer on lorry	Atlas AE 6000

Deconstruction processes

Bituminous bound materials, i.e. asphalt concrete and bituminous stabilised subbases, are deconstructed with a mill cutter, which can remove an asphalt pavement up to full depth and delivers asphalt aggregates, i.e. reclaimed asphalt pavement RAP, directly applicable as recycled material for asphalt production. The asphalt aggregates are loaded onto a transport lorry by the mill cutter.

Hydraulically bound materials, i.e. concrete and hydraulically stabilised subbases, are ruptured into bigger pieces by a hydraulic digger equipped with a bucket crusher. These pieces are loaded by another hydraulic digger onto a transport lorry for transportation to a recycling plant, where the concrete pieces are separated from anchor steel and crushed to recycled concrete granulates.

Unbound subbase is either reconstructed into a hydraulically or bituminous bound subbase in situ or loaded by a hydraulic digger onto a transport lorry and transported to further production processes. Table 7 shows all analysed processes and machines utilised for deconstruction materials.

Table 7. Processes and machines used for deconstruction processes.

Deconstruction process	Machine type	Analysed machine
Bituminous bound materials		
Milling	Mill cutter	Wirtgen W 200
Hydraulically bound materials		
Rupturing layer	Hydraulic digger with bucket crusher	CAT 330 D
Loading	Hydraulic digger	CAT 345 D
Unbound subbases		
Loading	Hydraulic digger	CAT 345 D

Recycling processes and allocation

For the production of new road material, reclaimed road material can be reused. After deconstructing the pavement layer the reclaimed material needs to be upgraded to a usable recycled material, which has the properties to substitute primary raw material. All road materials applied within pavements in Table 2 are 100% recyclable (ACPA, 2010; O'Sullivan, 2009).

The 'cut-off' rule regulates the allocation of the recycling processes that make material applicable for the reuse in material production. The 'cut' between the deconstruction process (system A) and material production process (system B) needs to be at a defined point. All recycling processes until this defined point are part of system A, and all processes after this point belong to system B (Klöpffer & Grahl, 2009). When an asphalt layer is deconstructed the mill cutter produces asphalt granulates that can be reused directly, i.e. the mill cutter is the recycling plant of the asphalt, from where it will be transported to storage. Road materials that need to be upgraded with a further process, e.g. concrete, are transported to a recycling plant after deconstruction, where they are processed and stored.

Therefore, for this study, the cut-off point between the deconstruction and production process is defined as the moment before the upgraded recycled material leaves its storage place and is transported to the production plant (Table 8).

Material transportation process

Materials for newly built pavements or reconstructed layers need to be transported from the production plant to the construction site during a maintenance intervention. Depending on the transport distance (TD), the empty weight (EW) and the load capacity (LC) of the transport lorry, transport processes are described in tonne-kilometres (Figure 1).

The tonne-kilometres for one transportation circulation (TC) can be described as followed:

$$TC = (EW + LC) * TD + EW * TD \qquad (1)$$

The number of transportation circulations (# of TC) needed for the production of one layer depends on the load capacity (LC) of the transport lorry, the width (w) and the length (l) of the pavement to be constructed, the thickness (t) of the layer and the density of the material during transport (D).

$$\#\text{ of }TC = (w * l * t) * D/LC \qquad (2)$$

Transportation distances generally depend on the location of the construction site. Expert opinions typically agree on 25 km as the average transport from a production plant to a construction site. If for bigger projects, e.g. highway construction, the material is mixed on site, the average transport distance was assumed to be 2.5 km.

The transport vehicle used depends on the material to be transported. Generally, all materials can be transported by a lorry. Some materials need to be

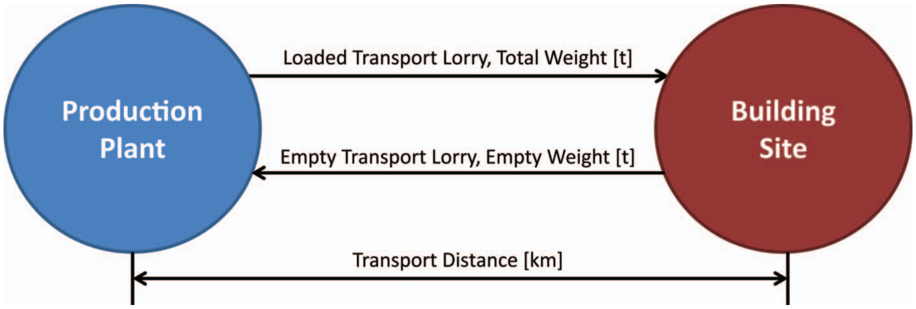

Figure 1. Material transportation scenario.

Table 8. Cut-off rule.

Process	Bituminous bound materials: *Asphalt layers* *Bituminous bound subbases*			Hydraulically bound materials: *Concrete layers* *Hydraulically bound subbases*			
	Process type	Machine type	Product/transport destination	Process type	Machine type	Product/transport destination	
Pavement/layer deconstruction	Milling	Milling machine	Asphalt granulates	Rupturing layer Loading	Hydraulic digger	Concrete pieces	
	Transport	Lorry	Storage	Transport	Lorry	Recycling plant and storage	
Upgrading to applicable recycled material	Was done during pavement deconstruction			Breaking	Crusher	Concrete granulates	
							Cut-off-point
Material production	Transport	Lorry	Production plant	Transport	Lorry	Production plant	
	Production processes		Bituminous bound material	Production processes		Hydraulically bound material	

covered during transport to retain the necessary material properties for the construction process. Concrete can optionally be transported with a truck mixer. It was assumed that five-axle lorries were used for all pavements for national roads, and that four-axle lorries were used for all cantonal roads. Furthermore it was assumed that all transport lorries fulfil the limits of the EURO 5 emission standard (European Parliament and Council of the European Union, 2007). Table 9 shows the properties of the transportation lorries analysed.

Table 9. Properties of transport lorries.

Lorry type	Load capacity (*t*)	Empty weight (*t*)	Total weight (*t*)	Emission standard
Five-axle	23.5	16.5	40	EURO 5
Four-axle	18	14	32	EURO 5

Quantification of inputs and outputs

The relevant inputs and outputs of the analysed processes, e.g. materials and fuels applied, emissions and waste products are quantified, i.e. a Life Cycle Inventory Analysis – LCI ((ISO *et al.*, 2006). Utilised machines were modelled based on producer data (Atlas, 2011; Caterpillar Inc., 2010; Lissmac, 2010; Weber, 2010; Wirtgen Group, 2010a, 2010b). Construction processes base on producer data of the applied machines, expert opinions and the ecoinvent database (Ecoinvent Center, 2010). All inputs and outputs for all modelled machines and construction processes can be found in Tables A1–A6 in the Appendix. For the modelling of the transport vehicles and processes, ecoinvent datasets were applied (Ecoinvent Center, 2010).

Weighting and assessment of in- and outputs according to environmental indicators

The inputs and outputs quantified in the previous step (energy, materials, emissions, etc) were weighted according to the selected environmental indicators, i.e. LCIA (ISO *et al.*, 2006).

Environmental indicators

Global warming potential (GWP) 2007

The IPCC GWP indicator (Intergovernmental Panel on Climate Change Global Warming Potential indicator) is an impact-orientated indicator, which takes all substances into account that contribute to climate change according to the guidelines of the IPCC (e.g. carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs) and sulphurhexafluoride (SF_6), etc.). The GWP of these substances is expressed in terms of an equivalent mass of carbon dioxide, i.e. kg-CO_2 equivalents. The atmospheric lifetime of a substance and its efficiency as a greenhouse gas are taken into account by the characterisation factors of the IPCC, which are utilised for the determination of the Global Warming Potential of the different substances, expressed in kg-CO_2 equivalents (see Table A7). Global warming potential is calculated for different time periods (20, 100 and 500 years). In this study, the Global Warming Potential was estimated for a period of 100 years, as required by the Kyoto protocol (Forster *et al.*, 2007).

Non-renewable CED (non-renewable)

The Non-Renewable CED is a resource-orientated indicator, which represents the direct and indirect consumption of fossil and nuclear energy sources, as well as biomass from primary forests over the life cycle of a product. The Non-renewable CED includes energy used during extraction, manufacturing and disposal of raw and auxiliary materials. Thereby, direct uses and indirect or grey consumption of energy resources due to the utilisation of, for example, asphalt as a construction material are considered. Characterisation factors for the aforementioned types of energy sources (fossil, nuclear, biomass primary forest) enable the expression of the result in terms of MJ equivalents (Table A8) (Boustead & Hancock, 1979; Ecoinvent Center, 2010).

Ecological scarcity 2006

The Swiss Ecological Scarcity method is an impact-orientated indicator and weights pollutant emissions and resource consumption, by utilising ‘eco-factors’. Eco-factors of different substances are deduced from environmental laws or corresponding political targets. The more the emissions or consumptions of resources exceed the environmental protection target, the higher the eco-factor (distance-to-target principle). The eco-factors are quantified as eco-points (Table A9, Frischknecht *et al.*, 2009).

Results

Pavements for national roads – traffic load class T6

Regarding material production processes Gschösser *et al.* (2011a) determined so called ‘best case’ pavements, i.e. those pavements whose production processes results in the lowest negative environmental impacts concerning the three analysed indicators. All given environmental potentials within the material production processes, i.e. recycling, production technology and alternative raw material potentials were considered. The work presented in this paper therefore was focused on the construction and maintenance processes of these pavements using materials produced with the lowest negative environmental impacts (Tables 10–13).

Table 10 presents the results for pavement construction, material transport and material production processes of the analysed pavements of the traffic load class T6 and the subgrade wearing capacity class S3 representative for all national road pavements analysed.

Due to the fact that for the construction of concrete and composite pavements more material needs to be processed, the values for all analysed indicators for the pavement construction processes of concrete and composite pavements are higher in comparison to processes needed for the construction of asphalt pavements. The GWP stemming from the pavement construction processes is 66% higher for the concrete pavement and 79% higher for the composite pavement in comparison to the construction of the analysed asphalt pavement. Concerning the Non-Renewable CED and the Ecological Scarcity indicator, concrete pavements cause a 60% and 74% higher negative impact and composite pavements a 72% and 88% higher negative impact. Analysing the construction processes, including all material transport to the construction site, shows even higher negative impacts for concrete and composite pavements, due to the fact that more material needs to be transported. For all three indicators analysed, all construction and transport processes for concrete pavements have 115% higher negative impacts than for the construction of asphalt pavements, and composite pavements have 130% higher impacts.

It can also be seen that the material production processes for asphalt pavements have the lowest GWP and Ecological Scarcity values, whereas the material production processes for concrete pavements have the lowest Non-Renewable CED values. Similar results were obtained for the new construction processes, where concrete pavements have a 135% and 86% higher GWP and Ecological Scarcity value than asphalt pavements, but a 17% lower Non-Renewable CED value than asphalt pavements. The results for the deconstruction, transportation and recycling processes of the different layers, a total replacement of the evaluated pavements was analysed (see Table 11).

The cut-off between the deconstruction and the material production processes was set at the moment before the applicable recycled material is transported from its storage to the material production. Since during the milling of asphalt layers the material is already broken into useable recycled material, only results for upgrade processes to applicable concrete granulate or granulates produced out of hydraulically bound subbases were estimated (see Table 11).

Due to the greater thickness of concrete and composite pavements, a greater amount of materials needs to be deconstructed, transported and upgraded, resulting in higher values for all three analysed indicators in comparison to asphalt pavement. The high influence of the upgrading process to usable recycled material for reclaimed concrete layers and hydraulically bound subbases can be seen in Table 11. Together with all deconstruction, upgrading and transportation processes, the full deconstruction of a concrete pavement when compared to the full deconstruction of an asphalt pavement has a 34% higher GWP value, a 35% higher Non-Renewable CED value and a 32% higher Ecological Scarcity value. The full deconstruction of composite pavement when compared to an asphalt pavement has 41% higher GWP and Non-Renewable CED values and a 38% higher Ecological Scarcity value.

Pavements for Cantonal roads – traffic load class T5 and T4

Tables 12 and 13 list the results for the pavements of the traffic load class T5 and the wearing capacity class S4, i.e. the two pavements that are representative of cantonal roads.

The new construction of concrete pavements has a 114% and 52% higher GWP and Ecological Scarcity values, but a 26% lower Non-Renewable CED value than asphalt pavements (shown in Table 12). Due to the fact that no subbase layer is required for concrete and composite pavements placed on subgrades of the wearing capacity class S4, the differences between the GWP and the Ecological Scarcity values for the new construction of asphalt and concrete pavements are smaller than for the T6 S3 class and larger with respect to the Non-Renewable CED values. Since for concrete and composite pavements of the traffic load class T6 also no subbase layer is required, this effect also occurs for highway pavements on subgrades of the class S4.

Due to the nearly equal thickness of both pavements, the differences between the indicator values for a full deconstruction of asphalt and concrete cantonal pavements are small (Table 13). The indicator values for concrete pavements are 4% (GWP), 5% (Non-Renewable CED) and 3% (Ecological Scarcity) higher than the results for asphalt pavements.

Influence of analysed processes and transport distances

The influence of the analysed processes for new built T6-S3 highway pavements was evaluated as representative for all pavements (Figure 2). As it can be seen in Figure 2 the material production processes have a significantly higher impact on the indicator values than

Table 10. Results new built highway pavement – T6 S3.

		Asphalt pavement					Concrete pavement					Composite pavement				
		Wearing course; AC MR 8 ASTRA; 30 mm	Base course; AC B 22 H; 70 mm	Road base; AC T 22 H; 80 mm	Subbase; hydraulically. bound; mixture; 160 mm	Sum	Wearing course; EA concrete; 50 mm	Concrete layer; bottom concrete; 190 mm	Interlayer; AC T 22 H; 80 mm	Subbase; crushed gravel; 120 mm	Sum	Wearing course; AC MR 8 ASTRA; 30 mm	Concrete layer; bottom concrete; 240 mm	Inter layer; AC T 22 H; 80 mm	Subbase; crushed gravel; 120 mm	Sum
Pavement construction (1)																
IPCC GWP 100a	t CO_2-eq/pm.	16	20	19	10	66	20	53	19	17	109	16	65	19	17	118
CED non-renewable	GJ-eq/pm.	282	347	324	187	1139	354	859	324	292	1829	282	1067	324	292	1964
Ecological scarcity	1,000,000 Pt/pm.	16	22	21	11	70	20	62	21	19	121	16	75	21	19	131
Material transport (2)																
IPCC GWP 100a	t CO_2-eq/pm.	90	221	254	16	582	154	592	254	284	1284	90	747	254	284	1376
CED non-renewable	GJ-eq/pm.	1537	3774	4332	281	9923	2631	10,095	4332	4852	21,910	1537	12,752	4332	4852	23,473
Ecological scarcity	1,000,000 Pt/pm.	79	193	222	14	508	135	517	222	248	1122	79	653	222	248	1202
(1) + (2)																
IPCC GWP 100a	t CO2-eq/pm.	106	242	273	27	647	174	645	273	302	1394	106	813	273	302	1494
CED Non-renewable	GJ-eq/pm.	1818	4121	4656	468	11,062	2985	10,954	4656	5144	23,739	1818	13,819	4656	5144	25,437
Ecological scarcity	1,000,000 Pt/pm.	95	215	242	25	578	155	578	242	267	1243	95	728	242	267	1333
Material production (3)																
IPCC GWP 100a	t CO_2-eq/pm.	997	1637	1430	1918	5982	2903	9657	1430	194	14,183	997	12,198	1430	194	14,818
CED non-renewable	GJ-eq/pm.	51,934	62,011	34,739	9789	158,473	18,686	57,491	34,739	5503	116,420	51,934	72,621	34,739	5503	164,797
Ecological scarcity	1,000,000 Pt/pm.	1396	2100	1445	1027	5968	2283	5557	1445	1677	10,962	1396	7019	1445	1677	11,537
(1) + (2) + (3)																
IPCC GWP 100a	t CO2-eq/pm.	1103	1879	1703	1945	6629	3077	10,301	1703	496	15,576	1103	13,011	1703	496	16,312
CED non-renewable	GJ-eq/pm.	53,752	66,132	39,395	10,256	169,535	21,671	68,446	39,395	10,648	140,158	53,752	86,439	39,395	10,648	190,234
Ecological scarcity	1,000,000 Pt/pm.	1491	2315	1687	1052	6546	2438	6136	1687	1944	12,205	1491	7748	1687	1944	12,871

Note: pm, Pavement.

Table 11. Results highway pavement deconstruction – T6 S3.

		Asphalt pavement					Concrete pavement					Composite pavement				
		Wearing course; AC MR 8 ASTRA; 30 mm	Base course; AC B 22 H; 70 mm	Road base; AC T 22 H; 80 mm	Subbase; hydraulically bituminous mixture; 160 mm	Sum	Wearing course; EA concrete; 50 mm	Concrete layer; Bottom concrete; 190 mm	Inter-layer; AC T 22 H; 80 mm	Subbase; crushed Gravel; 120 mm	Sum	Wearing course; AC MR 8 ASTRA; 30 mm	Concrete Layer; Bottom Concrete; 240 mm	Inter-layer; AC T 22 H; 80 mm	Subbase; crushed gravel; 120 mm	Sum
Pavement deconstruction (4)																
IPCC GWP 100a	t CO_2-eq/pm.	43			50	93	75		27	14	115	27	75	14	27	142
CED Non-renewable	GJ-eq/pm.	659			765	1424	1148		413	211	1772	404	1115	205	404	2127
Ecological scarcity	1,000,000 Pt/pm.	98			61	159	92		32	17	140	32	92	17	32	172
Material transport (5)																
IPCC GWP 100a	t CO_2-eq/pm.	79	184	211	421	895	132	500	211	269	1111	79	632	211	269	1190
CED Non-renewable	GJ-eq/pm.	1349	3145	3593	7187	15,274	2247	8533	3593	4582	18,955	1349	10,780	3593	4582	20,304
Ecological scarcity	1,000,000 Pt/pm.	69	161	184	368	782	115	437	184	235	971	69	552	184	235	1040
Material Upgrading (6)																
IPCC GWP 100a	t CO_2-eq/pm.	0	0	0	619	619	194	736	0	0	929	0	929	0	0	929
CED Non-renewable	GJ-eq/pm.	0	0	0	11,175	11,175	3492	13,270	0	0	16,762	0	16,762	0	0	16,762
Ecological scarcity	1,000,000 Pt/pm.	0	0	0	688	688	215	816	0	0	1031	0	1031	0	0	1031
(4) + (5) +(6)																
IPCC GWP 100a	t CO2-eq/pm.	517			1091	1608	1636		237	282	2155	106	1636	224	295	2261
CED Non-renewable	GJ-eq/pm.	8746			19,127	27,873	28,690		4006	4793	37,489	1752	28,657	3798	4985	39,193
Ecological scarcity	1,000,000 Pt/pm.	512			1117	1629	1675		216	251	2142	101	1675	201	266	2243

Note: pm, Pavement.

Table 12. Results new built pavement cantonal road – T5 S4.

		Asphalt pavement					Concrete pavement				
		Wearing course; AC MR 8; 30 mm	Base course; AC B 16 S; 60 mm	Road base; AC T 22 S; 60 mm	Subbase; hydraulically bituminous mixture; 160 mm	Sum	Wearing Course; EA Concrete; 50 mm	Concrete layer; bottom concrete; 150 mm	Inter-layer; AC T 22 N; 80 mm	Subbase; no Subbase	Sum
Pavement construction (7)											
IPCC GWP 100a	t CO_2-eq/pm.	0.3	0.4	0.4	0.2	1.2	0.3	0.6	0.3	0.0	1.2
CED Non-Renewable	GJ-eq/pm.	5.1	6.4	6.4	3.4	21.3	5.0	9.8	5.9	0.0	20.7
Ecological scarcity	1,000,000 Pt/pm.	0.3	0.4	0.4	0.2	1.3	0.3	0.7	0.4	0.0	1.4
Material transport (8)											
IPCC GWP 100a	t CO_2-eq/pm.	1.8	3.7	3.8	0.4	9.7	3.1	9.1	5.0	0.0	17.2
CED Non-renewable	GJ-eq/pm.	31.4	62.9	65.0	6.3	165.6	52.4	155.1	85.9	0.0	293.4
Ecological scarcity	1,000,000 Pt/pm.	1.6	3.2	3.3	0.3	8.5	2.7	7.9	4.4	0.0	15.0
(7) + (8)											
IPCC GWP 100a	t CO_2-eq/pm.	2.1	4.1	4.2	0.6	10.9	3.4	9.7	5.4	0.0	18.4
CED non-renewable	GJ-eq/pm.	36.6	69.2	71.3	9.7	186.8	57.4	164.9	91.8	0.0	314.1
Ecological scarcity	1,000,000 Pt/pm.	1.9	3.6	3.7	0.5	9.8	3.0	8.6	4.8	0.0	16.4
Material production (9)											
IPCC GWP 100a	t CO_2-eq/pm.	18.6	26.8	19.6	35.1	100.1	53.1	139.5	26.2	0.0	218.7
CED Non-renewable	GJ-eq/pm.	971.5	1064.4	476.6	179.1	2691.6	341.8	830.3	635.5	0.0	1807.5
Ecological scarcity	1,000,000 Pt/pm.	26.1	34.1	19.8	18.8	98.8	41.8	80.3	26.4	0.0	148.4
(7) + (8) + (9)											
IPCC GWP 100a	t CO2-eq/pm.	20.8	30.9	23.8	35.6	111.1	56.5	149.2	31.5	0.0	237.2
CED Non-renewable	GJ-eq/pm.	1008.1	1133.6	547.9	188.8	2878.4	399.2	995.1	727.3	0.0	2121.7
Ecological scarcity	1,000,000 Pt/pm.	28.0	37.7	23.5	19.3	108.6	44.7	88.9	31.2	0.0	164.9

Note: pm, Pavement.

Table 13. Results deconstruction cantonal road – T5 S4.

		Asphalt pavement					Concrete pavement				
		Wearing course; AC MR 8; 30 mm	Base course; AC B 16 S; 60 mm	Road base; AC T 22 S; 60 mm	Subbase; hydrauclically bituminous mixture; 160 mm	Sum	Wearing course; EA concrete; 50 mm	Concrete layer; bottom concrete; 150 mm	Inter-layer; AC T 22 N; 80 mm	Subbase; no Subbase	Sum
Pavement deconstruction (10)											
IPCC GWP 100a	t CO_2-eq/pm.	0.8			0.9	1.7	1.1		0.5	0.0	1.6
CED non-renewable	GJ-eq/pm.	12.0			14.0	26.0	17.5		7.6	0.0	25.1
Ecological scarcity	1,000,000 Pt/pm.	1.8			1.1	2.9	1.4		0.6	0.0	2.0
Material transport (11)											
IPCC GWP 100a	t CO_2-eq/pm.	1.6	3.1	3.1	8.2	16.0	2.6	7.7	4.2	0.0	14.5
CED Non-Renewable	GJ-eq/pm.	27.2	52.4	52.4	140.4	272.4	44.0	132.0	71.3	0.0	247.3
Ecological Scarcity	1,000,000 Pt/pm.	1.4	2.7	2.7	7.2	13.9	2.3	6.8	3.6	0.0	12.7
Material upgrading (12)											
IPCC GWP 100a	t CO_2-eq/pm.	0.0	0.0	0.0	11.3	11.3	3.5	10.6	0.0	0.0	14.2
CED Non-renewable	GJ-eq/pm.	0.0	0.0	0.0	204.4	204.4	63.9	191.6	0.0	0.0	255.5
Ecological scarcity	1,000,000 Pt/pm.	0.0	0.0	0.0	12.6	12.6	3.9	11.8	0.0	0.0	15.7
(10) + (11) + (12)											
I PCC GWP 100a	t CO2-eq/pm.	8.5			20.5	29.0	25.6		4.7	0.0	30.3
CED non-renewable	GJ-eq/pm.	144.1			358.8	502.9	449.1		78.8	0.0	527.9
Ecological scarcity	1,000,000 Pt/pm.	8.6			20.9	29.4	26.1		4.2	0.0	30.4

Note: pm, Pavement.

the material transport or pavement construction processes, e.g. up to 93%, when a highway pavement is newly built. For an average material transport distance of 25 km, transport processes have an average influence of 9%. A reduction of the transport distance from 25 to 5 km would reduce the impact of transport processes to 2% on average, and an increase from 25 to 40 km would increase the impact of the transport processes to 14% on average. The impact of the construction processes is small, 1% on average.

The influence of all processes needed to fully replace highway pavements of the categories T6-S3 can be seen in Figure 3. The material production processes have the largest impact, (up to 80% when a highway pavement is fully replaced) and the upgrading processes of the recycled material have the second largest impact (10% on average). For an average material transport distance of 25 km, both material transports of construction and deconstructed materials have an average impact of 8%. A reduction to 5 km would reduce the impact of both transport processes to 2% on average and an increase to 40 km would increase the impact of the transportation processes to 11.5% on average. The influence of the construction and deconstruction processes is small (1% on average).

Due to the little influence of construction and deconstruction processes on the overall results for new built and fully replaced pavements, no sensitivity analyses considering alternative construction and

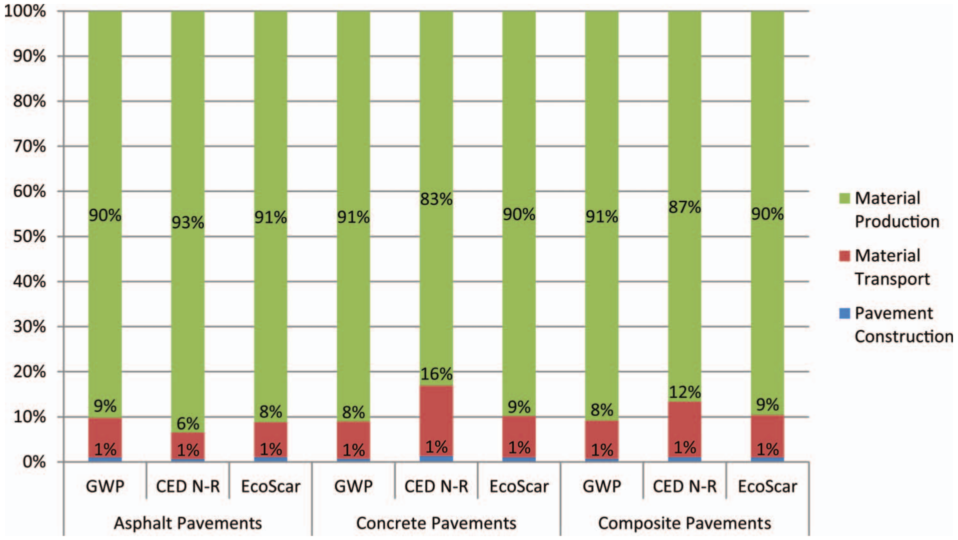

Figure 2. Influence of analysed processes for new built national roads T6-S3.

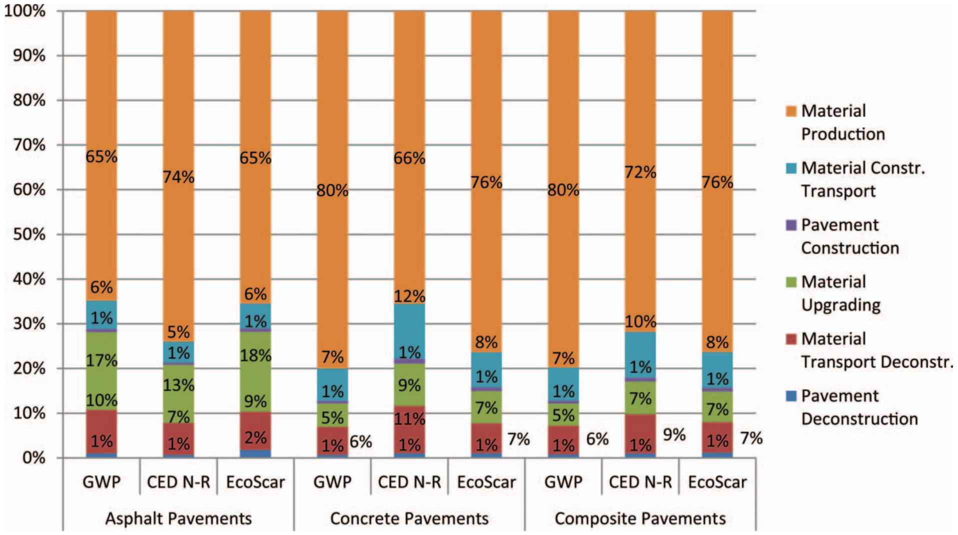

Figure 3. Influence of analysed processes for replacement of T6-S3 pavements.

deconstruction processes utilising alternative building machines were carried out.

Monte Carlo simulation

To determine the reliability of the results in Tables 10–13, Monte Carlo simulations were performed. To perform the Monte Carlo simulations standard deviations for every life cycle inventory entry (input and output) were estimated. For information (LCI) taken from the ecoinvent database, the standard deviation was taken as given in ecoinvent. The standard deviation for new determined data is based on the ecoinvent pedigree approach (Ecoinvent Center, 2010). The standard deviations applied for these Monte Carlo simulations can be found in Gschösser (2011). The Monte Carlo simulations estimate the 95% confidence interval of the cumulative LCA results by selected values within the uncertainty range defined for every inventory entry and running a specified number of simulations (Ries, 2003; Wang, Chang, & El-Sheikh, 2011). In this investigation, 1000 Monte Carlo runs were deemed sufficient. The comparison of the 95% confidence interval of the LCA results of two pavement types (Figure 4) shows the probability that the indicator value of pavement type A is larger than the indicator value of alternative B.

The results of the Monte Carlo simulations show that the conclusions with respect to which pavement type has construction and maintenance processes that have lower environmental impact indicator values than another are reliable (Figure 4), with the exception of the ranking done using the Non-Renewable CED indicator for the new construction processes of asphalt and concrete pavements. This is due to the small difference between the CED values for the asphalt and the concrete processes.

Comparison to related studies

In order to prove the reliability with regard to related studies the results for all processes needed for the new construction of asphalt pavements were compared to the results of Mroueh *et al*. (2000) and Weiland (2008). Mroueh *et al*. (2000) analysed an asphalt pavement consisting of 160 mm asphalt concrete and 750 mm unbound subbase with a width of 7.5 m. Thus, this study is comparable to the analysis of cantonal roads. Weiland (2008) analysed an asphalt highway pavement with 325 mm of asphalt concrete which is placed on an existing subbase. Thus, this study is compared to results of the analysis of national roads.

The results in the related studies are expressed in terms of CO_2 emissions and energy, which can cause uncertainties in the comparisons to the results of this study where results are expressed as CO_2 and MJ equivalents. Weiland (2008) applied LCI data from the US Environmental Protection Agency's NONROAD model (USEPA 2005). Mroueh *et al*. (2000) used secondary LCI data from literature published between 1989 and 1999.

The comparison shows that the results of this study are in the same range as the results of the related studies (Table 14). The differences between the results regarding the energy consumption can be explained by the fact that energy use calculated for the related studies does not include the feedstock energy of the bitumen applied in the asphalt mixtures. The little lower CO_2 emissions of the pavement analysed by Weiland (2008) can be explained by the fact that no subbase layer was analysed and that only pure CO_2 emissions and not the IPCC Global Warming Potential, which contains all substances that contribute to climate change, were used as environmental indicator. Results for the pavement analysed by Weiland (2008)

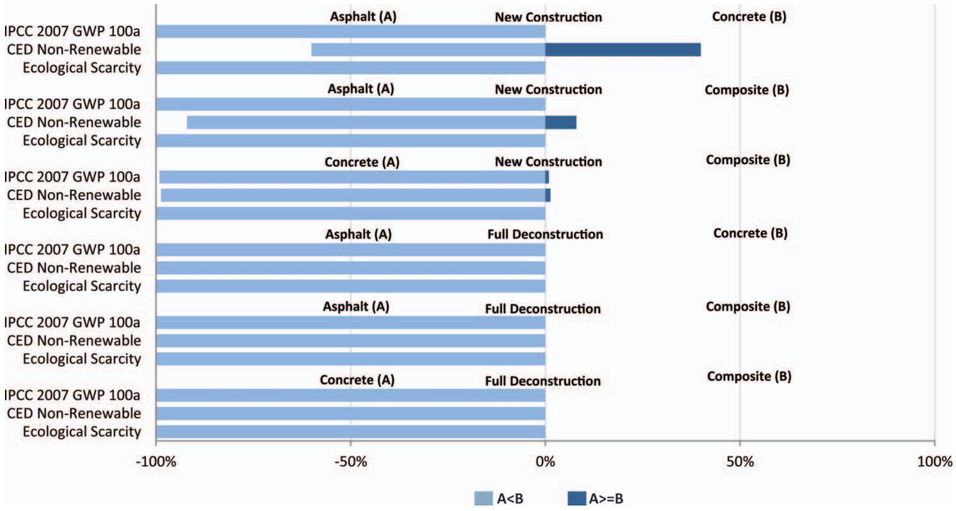

Figure 4. Results of Monte Carlo simulation.

including a subbase layer would cause higher values for IPCC GWP 2007 indicator, due to the higher negative impacts of, for example, electricity production and material production in comparison to the Swiss situation.

Table 14. Comparison to related studies.

		Cantonal roads		National roads	
		Mroueh et al. (2000)	T5-S4	Weiland (2008)	T6-S3
New Construction					
CO_2/GWP	t CO_2/pm.	–	111	6477	6629
Energy/CED	GJ/pm.	2579	2878	122,158	169,535

Note: pm, pavement.

Conclusions

It has been shown in this study that for all analysed processes, the material production has the biggest impact on the values of the three analysed environmental indicators, i.e. this is the most influential life-cycle phase of a road pavement. Future research aimed at reducing the environmental impact of pavements should be focused on the material production processes.

Concrete and composite pavements have lower negative environmental impact when they are placed on subgrades of wearing capacity S4, due to the fact that no subbase layer is required, when compared to subgrades that require a subbase layer. There is little impact due to the pavement construction and deconstruction processes when compared to those of the other analysed processes and therefore these processes considered little to the environmental performance of road pavements.

One of the most interesting areas of future research could be the application of a reverse engineering approach for the determination of the thickness of concrete and composite pavements that would offer the same environmental performance with respect to the GWP and the Ecological Scarcity indicators, taking into consideration the effects on wearing capacity, life time, and maintenance requirements.

Furthermore, future research should analyse the performance of road pavements over different time periods taking into consideration the different deterioration rates and different intervention strategies, to obtain a complete view of the impact of a road section on the environment. In such research it would also be interesting to investigate the impact of the interventions on vehicle behaviour during the maintenance interventions, e.g. when alternative routeing causes travel distances for the whole traffic load, as well as processes during operation, such as vehicle operation and fuel consumption, lightning, road cleaning, albedo, carbonation and noise generation, which could change the outcome of this study.

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Appendix

Table A1. Modelled building machine.

	Construction						Deconstruction			
Building machine Model	Slip Form Paver Wirtgen SP 1200	Asphalt Paver CAT AP555 E	Single Drum Smooth CAT CS 74	Wheel Loader CAT 906 H	Joint Cutter Lissmac FS 31 D	Vibration Plate Weber CR10	Hydraulic Digger CAT 345D	Hydraulic Digger CAT 330D	Mill Cutter Wirtgen W200	Unit
Weight	70.0	16.7	15.5	5.7	0.9	0.9	52.2	42.4	24.9	t
Materials/fuels										
Electricity, medium voltage	64,867	15,517	14,322	5275	843	834	48,400	39,254	23,074	kWh
Natural gas, burned in industrial furnace	700,000	167,450	154,550	56,920	9,100	9,000	522,300	423,600	249,000	MJ
Reinforcing steel	49,000	11,722	10,819	3,984	637	630	36,561	29,652	17,430	kg
Steel, low-alloyed	21,000	5,024	4,637	1,708	273	270	15,669	12,708	7,470	kg
Transport, freight, rail	14,000	3,349	3,091	1,138	182	180	10,446	8,472	4,980	tkm
Transport, lorry 20–28t	1.6	0.4	0.4	0.1	0.0	0.0	1.2	1.0	0.6	tkm
Transport, lorry > 28t	7,000	1,675	1,546	569	91	90	5,223	4,236	2,490	tkm
Emissions to air										
Heat, waste	233,333	55,817	51,517	18,973	3,033	3,000	174,100	141,200	83,000	MJ

Table A2. Modelled processes for construction of asphalt layers and warm and cold bituminous bound subbases.

	Paving							
Process	Wearing course	Base course	Road base	Bitumen Bound subbases	Rolling	Compacting	Spraying bitumen emulsion	Unit per m^2
Materials/fuels								
Lubricating Oil	0.0028	0.0028	0.0028	0.0028	0.0026	0.0002		kg
Building Machine*	2.55E-08	5.96E-08	6.81E-08	1.11E-07	8.24E-09	1.30E-07		p
Diesel	0.0040	0.0094	0.0108	0.0175	0.0011	0.0011	0.0001	kg
Emissions to air								
Ammonia	8.05E-08	1.88E-07	2.15E-07	3.49E-07	2.19E-08	2.16E-08	1.57E-09	kg
Benzo(a)pyrene	1.21E-10	2.82E-10	3.22E-10	5.24E-10	3.28E-11	3.24E-11	2.36E-12	kg
Cadmium	4.04E-11	9.43E-11	1.08E-10	1.75E-10	1.10E-11	1.08E-11	7.90E-13	kg
Carbon dioxide, fossil	1.26E-02	2.94E-02	3.36E-02	5.45E-02	3.42E-03	3.37E-03	2.46E-04	kg
Carbon monoxide, fossil	4.60E-05	1.07E-04	1.23E-04	1.99E-04	1.25E-05	1.23E-05	8.98E-07	kg
Chromium	2.01E-10	4.70E-10	5.37E-10	8.73E-10	5.47E-11	5.40E-11	3.94E-12	kg
Copper	6.85E-09	1.60E-08	1.83E-08	2.97E-08	1.86E-09	1.83E-09	1.34E-10	kg
Dinitrogen monoxide	4.84E-07	1.13E-06	1.29E-06	2.10E-06	1.32E-07	1.30E-07	9.46E-09	kg
Dioxins	2.42E-16	5.64E-16	6.45E-16	1.05E-15	6.57E-17	6.48E-17	4.73E-18	kg
Heat, waste	1.83E-01	4.26E-01	4.87E-01	7.91E-01	4.96E-02	4.89E-02	3.57E-03	MJ
Methane, fossil	6.45E-07	1.50E-06	1.72E-06	2.79E-06	1.75E-07	1.73E-07	1.26E-08	kg
Nickel	2.82E-10	6.57E-10	7.51E-10	1.22E-09	7.65E-11	7.54E-11	5.50E-12	kg
Nitrogen oxides	1.78E-04	4.15E-04	4.74E-04	7.70E-04	4.83E-05	4.76E-05	3.47E-06	kg

(*continued*)

Table A2. (*Continued*).

Process	Paving				Rolling	Compacting	Spraying bitumen emulsion	Unit per m^2
	Wearing course	Base course	Road base	Bitumen Bound subbases				
Non-methane volatile organic compounds	2.09E-05	4.87E-05	5.56E-05	9.04E-05	5.66E-06	5.59E-06	4.07E-07	kg
Polycyclic aromatic hydrocarbons	1.35E-08	3.16E-08	3.61E-08	5.87E-08	3.68E-09	3.63E-09	2.65E-10	kg
Particulates, $<2.5\ \mu m$	1.63E-05	3.79E-05	4.34E-05	7.04E-05	4.42E-06	4.35E-06	3.18E-07	kg
Selenium	4.04E-11	9.43E-11	1.08E-10	1.75E-10	1.10E-11	1.08E-11	7.90E-13	kg
Sulphur dioxide	4.07E-06	9.50E-06	1.09E-05	1.76E-05	1.11E-06	1.09E-06	7.96E-08	kg
Zinc	4.04E-09	9.43E-09	1.08E-08	1.75E-08	1.10E-09	1.08E-09	7.90E-11	kg
Particulates, $>10\ \mu m$	1.08E-06	2.53E-06	2.89E-06	4.69E-06	2.94E-07	2.90E-07	2.12E-08	kg
Particulates, $>2.5\ \mu m$, and $<10\ \mu m$	7.22E-07	1.68E-06	1.92E-06	3.13E-06	1.96E-07	1.93E-07	1.41E-08	kg
Waste to treatment								
Disposal, used mineral oil	0.0028	0.0028	0.0028	0.0028	0.0026	0.0002		kg

Note: *See Table A1.

Table A3. Modelled processes for construction of concrete layers.

Process	Distribution bottom concrete, T6	Paving bottom concrete			Paving EA concrete		Cutting joints		Brushing EA Surface	Unit per m^2
		T6	T5	T4	T6	T5 and T4	T6	T5 and T4		
Materials/fuels										
Lubricating oil	0.0009	0.0117	0.0075	0.0075	0.0117	0.0075	5.99E-05	5.06E-05	1.52E-04	kg
Building machine*	1.62E-07	1.62E-07	1.28E-07	1.02E-07	4.26E-08	4.26E-08	2.20E-08	1.85E-08	8.71E-09	p
Diesel	0.0081	0.0404	0.0319	0.0255	0.0106	0.0106	0.0002	0.0002	0.0004	kg
Emissions to air										
Ammonia	1.61E-07	8.05E-07	6.36E-07	5.08E-07	2.12E-07	2.12E-07	3.64E-09	3.07E-09	8.67E-09	kg
Benzo(a)pyrene	2.42E-10	1.21E-09	9.55E-10	7.64E-10	3.18E-10	3.18E-10	5.47E-12	4.62E-12	1.30E-11	kg
Cadmium	8.08E-11	4.04E-10	3.19E-10	2.55E-10	1.06E-10	1.06E-10	1.83E-12	1.54E-12	4.35E-12	kg
Carbon dioxide, fossil	2.52E-02	1.26E-01	9.94E-02	7.95E-02	3.31E-02	3.31E-02	5.69E-04	4.80E-04	1.36E-03	kg
Carbon monoxide, fossil	9.19E-05	4.60E-04	3.63E-04	2.90E-04	1.21E-04	1.21E-04	2.08E-06	1.75E-06	4.95E-06	kg
Chromium	4.03E-10	2.01E-09	1.59E-09	1.27E-09	5.30E-10	5.30E-10	9.11E-12	7.69E-12	2.17E-11	kg
Copper	1.37E-08	6.85E-08	5.41E-08	4.33E-08	1.80E-08	1.80E-08	3.10E-10	2.61E-10	7.38E-10	kg
Dinitrogen monoxide	9.69E-07	4.84E-06	3.82E-06	3.06E-06	1.27E-06	1.27E-06	2.19E-08	1.85E-08	5.22E-08	kg
Dioxins	4.84E-16	2.42E-15	1.91E-15	1.53E-15	6.36E-16	6.36E-16	1.09E-17	9.23E-18	2.61E-17	kg
Heat, waste	3.65E-01	1.83E + 00	1.44E + 00	1.15E + 00	4.81E-01	4.81E-01	8.26E-03	6.97E-03	1.97E-02	MJ
Methane, fossil	1.29E-06	6.45E-06	5.09E-06	4.07E-06	1.70E-06	1.70E-06	2.92E-08	2.46E-08	6.95E-08	kg
Nickel	5.63E-10	2.82E-09	2.22E-09	1.78E-09	7.41E-10	7.41E-10	1.27E-11	1.08E-11	3.03E-11	kg
Nitrogen oxides	3.55E-04	1.78E-03	1.40E-03	1.12E-03	4.68E-04	4.68E-04	8.04E-06	6.78E-06	1.91E-05	kg
Non-methane volatile organic compounds	4.17E-05	2.09E-04	1.65E-04	1.32E-04	5.49E-05	5.49E-05	9.44E-07	7.96E-07	2.25E-06	kg
Polycyclic aromatic hydrocarbons	2.71E-08	1.35E-07	1.07E-07	8.55E-08	3.56E-08	3.56E-08	6.13E-10	5.17E-10	1.46E-09	kg
Particulates, $<2.5\ \mu$m	3.25E-05	1.63E-04	1.28E-04	1.03E-04	4.28E-05	4.28E-05	7.36E-07	6.21E-07	1.75E-06	kg
Selenium	8.08E-11	4.04E-10	3.19E-10	2.55E-10	1.06E-10	1.06E-10	1.83E-12	1.54E-12	4.35E-12	kg
Sulphur dioxide	8.14E-06	4.07E-05	3.21E-05	2.57E-05	1.07E-05	1.07E-05	1.84E-07	1.55E-07	4.39E-07	kg
Zinc	8.08E-09	4.04E-08	3.19E-08	2.55E-08	1.06E-08	1.06E-08	1.83E-10	1.54E-10	4.35E-10	kg
Particulates, $>10\ \mu$m	2.17E-06	1.08E-05	8.55E-06	6.84E-06	2.85E-06	2.85E-06	4.90E-08	4.13E-08	1.17E-07	kg
Particulates, $>2.5\ \mu$m, and $<10\ \mu$m	1.44E-06	7.22E-06	5.70E-06	4.56E-06	1.90E-06	1.90E-06	3.27E-08	2.76E-08	7.78E-08	kg
Waste to treatment										
Disposal, used mineral oil	0.0009	0.0117	0.0075	0.0075	0.0117	0.0075	0.0001	0.0001	0.0002	kg

Note: *See Table A1.

Table A4. Modelled processes for construction of hydraulically bound subbases.

Process	Distributing				Rolling	Compacting	Spraying bit. emulsion	Unit per m^2
	200 mm	170 mm	160 mm	150 mm				
Materials/fuels								
Lubricating oil	0.0016	0.0016	0.0016	0.0016	0.0026	0.0002		kg
Building machine*	1.70E-07	1.45E-07	1.36E-07	1.28E-07	8.24E-09	1.30E-07		p
Diesel	0.0176	0.0149	0.0141	0.0132	0.0011	0.0011	0.0001	kg
Emissions to air								
Ammonia	3.50E-07	2.98E-07	2.80E-07	2.63E-07	2.19E-08	2.16E-08	1.57E-09	kg
Benzo(a)pyrene	5.26E-10	4.47E-10	4.21E-10	3.95E-10	3.28E-11	3.24E-11	2.36E-12	kg
Cadmium	1.76E-10	1.49E-10	1.41E-10	1.32E-10	1.10E-11	1.08E-11	7.90E-13	kg
Carbon dioxide, fossil	5.48E-02	4.65E-02	4.38E-02	4.11E-02	3.42E-03	3.37E-03	2.46E-04	kg
Carbon monoxide, fossil	2.00E-04	1.70E-04	1.60E-04	1.50E-04	1.25E-05	1.23E-05	8.98E-07	kg
Chromium	8.76E-10	7.45E-10	7.01E-10	6.57E-10	5.47E-11	5.40E-11	3.94E-12	kg
Copper	2.98E-08	2.53E-08	2.38E-08	2.23E-08	1.86E-09	1.83E-09	1.34E-10	kg
Dinitrogen monoxide	2.11E-06	1.79E-06	1.69E-06	1.58E-06	1.32E-07	1.30E-07	9.46E-09	kg
Dioxins	1.05E-15	8.94E-16	8.42E-16	7.89E-16	6.57E-17	6.48E-17	4.73E-18	kg
Heat, waste	7.95E-01	6.75E-01	6.36E-01	5.96E-01	4.96E-02	4.89E-02	3.57E-03	MJ
Methane, fossil	2.81E-06	2.38E-06	2.24E-06	2.10E-06	1.75E-07	1.73E-07	1.26E-08	kg
Nickel	1.23E-09	1.04E-09	9.80E-10	9.19E-10	7.65E-11	7.54E-11	5.50E-12	kg
Nitrogen oxides	7.73E-04	6.57E-04	6.18E-04	5.80E-04	4.83E-05	4.76E-05	3.47E-06	kg
Non-methane volatile organic compounds	9.07E-05	7.71E-05	7.26E-05	6.80E-05	5.66E-06	5.59E-06	4.07E-07	kg
Polycyclic aromatic hydrocarbons	5.89E-08	5.01E-08	4.71E-08	4.42E-08	3.68E-09	3.63E-09	2.65E-10	kg
Particulates, <2.5 μm	7.07E-05	6.01E-05	5.66E-05	5.30E-05	4.42E-06	4.35E-06	3.18E-07	kg
Selenium	1.76E-10	1.49E-10	1.41E-10	1.32E-10	1.10E-11	1.08E-11	7.90E-13	kg
Sulphur dioxide	1.77E-05	1.51E-05	1.42E-05	1.33E-05	1.11E-06	1.09E-06	7.96E-08	kg
Zinc	1.76E-08	1.49E-08	1.41E-08	1.32E-08	1.10E-09	1.08E-09	7.90E-11	kg
Particulates, >10 μm	4.71E-06	4.00E-06	3.77E-06	3.53E-06	2.94E-07	2.90E-07	2.12E-08	kg
Particulates, >2.5 μm, and <10 μm	3.14E-06	2.67E-06	2.51E-06	2.36E-06	1.96E-07	1.93E-07	1.41E-08	kg
Waste to treatment								
Disposal, used mineral oil	0.0016	0.0016	0.0016	0.0016	0.0026	0.0002		kg

Note: *See Table A1.

Table A5. Modelled processes for construction of unbound bound subbases.

Process	Distributing				Rolling	Compacting	Unit per m^2
	200 mm	160 mm	150 mm	120 mm			
Materials/fuels							
Lubricating oil	0.0016	0.0016	0.0016	0.0016	0.0026	0.0002	kg
Building machine*	1.28E-07	1.02E-07	9.57E-08	7.66E-08	8.24E-09	1.30E-07	p
Diesel	0.0132	0.0105	0.0099	0.0079	0.0011	0.0011	kg
Emissions to air							
Ammonia	2.63E-07	2.10E-07	1.97E-07	1.58E-07	2.19E-08	2.16E-08	kg
Benzo(a)pyrene	3.95E-10	3.16E-10	2.96E-10	2.37E-10	3.28E-11	3.24E-11	kg
Cadmium	1.32E-10	1.05E-10	9.89E-11	7.91E-11	1.10E-11	1.08E-11	kg
Carbon dioxide, fossil	4.11E-02	3.29E-02	3.08E-02	2.46E-02	3.42E-03	3.37E-03	kg
Carbon monoxide, fossil	1.50E-04	1.20E-04	1.12E-04	9.00E-05	1.25E-05	1.23E-05	kg
Chromium	6.57E-10	5.26E-10	4.93E-10	3.94E-10	5.47E-11	5.40E-11	kg
Copper	2.23E-08	1.79E-08	1.68E-08	1.34E-08	1.86E-09	1.83E-09	kg
Dinitrogen monoxide	1.58E-06	1.26E-06	1.19E-06	9.48E-07	1.32E-07	1.30E-07	kg
Dioxins	7.89E-16	6.31E-16	5.92E-16	4.73E-16	6.57E-17	6.48E-17	kg
Heat, waste	5.96E-01	4.77E-01	4.47E-01	3.58E-01	4.96E-02	4.89E-02	MJ
Methane, Fossil	2.10E-06	1.68E-06	1.58E-06	1.26E-06	1.75E-07	1.73E-07	kg
Nickel	9.19E-10	7.35E-10	6.89E-10	5.51E-10	7.65E-11	7.54E-11	kg
Nitrogen oxides	5.80E-04	4.64E-04	4.35E-04	3.48E-04	4.83E-05	4.76E-05	kg
Non-methane volatile organic compounds	6.80E-05	5.44E-05	5.10E-05	4.08E-05	5.66E-06	5.59E-06	kg

(*continued*)

Table A5. (*Continued*).

Process	Distributing				Rolling	Compacting	Unit per m^2
	200 mm	160 mm	150 mm	120 mm			
Polycyclic aromatic hydrocarbons	4.42E-08	3.54E-08	3.31E-08	2.65E-08	3.68E-09	3.63E-09	kg
Particulates, <2.5 μm	5.30E-05	4.24E-05	3.98E-05	3.18E-05	4.42E-06	4.35E-06	kg
Selenium	1.32E-10	1.05E-10	9.89E-11	7.91E-11	1.10E-11	1.08E-11	kg
Sulphur dioxide	1.33E-05	1.06E-05	9.97E-06	7.97E-06	1.11E-06	1.09E-06	kg
Zinc	1.32E-08	1.05E-08	9.89E-09	7.91E-09	1.10E-09	1.08E-09	kg
Particulates, >10 μm	3.53E-06	2.83E-06	2.65E-06	2.12E-06	2.94E-07	2.90E-07	kg
Particulates, >2.5 μm and <10 μm	2.36E-06	1.88E-06	1.77E-06	1.41E-06	1.96E-07	1.93E-07	kg
Waste to treatment							
Disposal, used mineral oil	0.0016	0.0016	0.0016	0.0016	0.0026	0.0002	kg

Note: *See Table A1.

Table A6. Modelled deconstruction processes.

Process	Milling asphalt				Unit per m^2	Hydraulically bound materials		Unbound Materials Loading	Unit per m^3
	WC	WC + BC	WC+BC + RB	Full Depth		Rupturing	Loading		
Materials/Fuels									
Lubricating oil	0.0042	0.0042	0.0042	0.0042	kg	0.0087	0.0071	0.0087	kg
Building machine*	8.80E-08	8.80E-08	8.80E-08	8.80E-08	p	5.88E-07	5.88E-07	4.00E-07	p
Diesel	0.0293	0.0394	0.0509	0.0726	kg	0.1862	0.1715	0.1266	kg
Emissions to air									
Ammonia	5.84E-07	7.85E-07	1.02E-06	1.45E-06	kg	3.71E-06	3.42E-06	2.52E-06	kg
Benzo(a)pyrene	8.77E-10	1.18E-09	1.52E-09	2.17E-09	kg	5.57E-09	5.13E-09	3.79E-09	kg
Cadmium	2.93E-10	3.94E-10	5.09E-10	7.26E-10	kg	1.86E-09	1.72E-09	1.27E-09	kg
Carbon dioxide, fossil	9.13E-02	1.23E-01	1.59E-01	2.26E-01	kg	5.80E-01	5.34E-01	3.94E-01	kg
Carbon monoxide, fossil	3.34E-04	4.48E-04	5.79E-04	8.25E-04	kg	2.12E-03	1.95E-03	1.44E-03	kg
Chromium	1.46E-09	1.96E-09	2.54E-09	3.62E-09	kg	9.28E-09	8.55E-09	6.31E-09	kg
Copper	4.97E-08	6.68E-08	8.63E-08	1.23E-07	kg	3.16E-07	2.91E-07	2.15E-07	kg
Dinitrogen Monoxide	3.51E-06	4.72E-06	6.11E-06	8.70E-06	kg	2.23E-05	2.06E-05	1.52E-05	kg
Dioxins	1.75E-15	2.36E-15	3.05E-15	4.34E-15	kg	1.11E-14	1.03E-14	7.58E-15	kg
Heat, waste	1.33E + 00	1.78E + 00	2.30E + 00	3.28E + 00	MJ	8.41E + 00	7.75E + 00	5.72E + 00	MJ
Methane, fossil	4.68E-06	6.29E-06	8.13E-06	1.16E-05	kg	2.97E-05	2.74E-05	2.02E-05	kg
Nickel	2.04E-09	2.75E-09	3.55E-09	5.06E-09	kg	1.30E-08	1.20E-08	8.82E-09	kg
Nitrogen oxides	1.29E-03	1.73E-03	2.24E-03	3.19E-03	kg	8.19E-03	7.54E-03	5.57E-03	kg
Non-methane volatile organic compounds	1.51E-04	2.03E-04	2.63E-04	3.74E-04	kg	9.61E-04	8.85E-04	6.53E-04	kg
Polycyclic aromatic hydrocarbons	9.83E-08	1.32E-07	1.71E-07	2.43E-07	kg	6.24E-07	5.75E-07	4.24E-07	kg
Particulates, <2.5 μm	1.18E-04	1.59E-04	2.05E-04	2.92E-04	kg	7.49E-04	6.90E-04	5.09E-04	kg
Selenium	2.93E-10	3.94E-10	5.09E-10	7.26E-10	kg	1.86E-09	1.72E-09	1.27E-09	kg
Sulphur dioxide	2.95E-05	3.97E-05	5.13E-05	7.31E-05	kg	1.88E-04	1.73E-04	1.28E-04	kg
Zinc	2.93E-08	3.94E-08	5.09E-08	7.26E-08	kg	1.86E-07	1.72E-07	1.27E-07	kg
Particulates, >10 μm	7.86E-06	1.06E-05	1.37E-05	1.94E-05	kg	4.99E-05	4.60E-05	3.39E-05	kg
Particulates, >2.5 μm, and <10um	5.24E-06	7.04E-06	9.10E-06	1.30E-05	kg	3.33E-05	3.06E-05	2.26E-05	kg
Waste to treatment									
Disposal, Used Mineral Oil	0.0042	0.0042	0.0042	0.0042	kg	0.0087	0.0071	0.0087	kg

Note: WC, Wearing course; BC, Base course; RB, Road base. *See Table A1.

Table A7. Characterisation Factors IPCC Global Warming Potential 2007 Indicator.

Substance	Unit	IPCC GWP 100a kg CO2-eq
Carbon dioxide, fossil	kg	1.00E + 00
Carbon dioxide, land transformation	kg	1.00E + 00
Carbon monoxide, fossil	kg	1.57E + 00
Chloroform	kg	3.00E + 01
Dinitrogen monoxide	kg	2.98E + 02
Ethane, 1,1,1,2-tetrafluoro-, HFC-134a	kg	1.43E + 03
Ethane, 1,1,1-trifluoro-, HFC-143a	kg	4.47E + 03
Ethane, 1,1,2-trichloro-1,2,2-trifluoro-, CFC-113	kg	6.13E + 03
Ethane, 1,1-dichloro-1-fluoro-, HCFC-141b	kg	7.25E + 02
Ethane, 1,1-difluoro-, HFC-152a	kg	1.24E + 02
Ethane, 1,2-dichloro-1,1,2,2-tetrafluoro-, CFC-114	kg	1.00E + 03
Ethane, 1-chloro-1,1-difluoro-, HCFC-142b	kg	2.31E + 03
Ethane, 2,2-dichloro-1,1,1-trifluoro-, HCFC-123	kg	7.70E + 02
Ethane, 2-chloro-1,1,1,2-tetrafluoro-, HCFC-124	kg	6.09E + 02
Ethane, chloropentafluoro-, CFC-115	kg	1.37E + 07
Ethane, hexafluoro-, HFC-116	kg	1.22E + 04
Ethane, pentafluoro-, HFC-125	kg	3.50E + 03
Methane, biogenic	kg	2.50E + 01
Methane, bromo-, Halon 1001	kg	5.00E + 00
Methane, bromochlorodifluoro-, Halon 1211	kg	1.89E + 03
Methane, bromotrifluoro-, Halon 1301	kg	7.14E + 03
Methane, chlorodifluoro-, HCFC-22	kg	1.81E + 03
Methane, chlorotrifluoro-, CFC-13	kg	1.44E + 04
Methane, dichloro-, HCC-30	kg	8.70E + 01
Methane, dichlorodifluoro-, CFC-12	kg	1.09E + 04
Methane, dichlorofluoro-, HCFC-21	kg	2.10E + 02
Methane, difluoro-, HFC-32	kg	6.75E + 02
Methane, fossil	kg	2.50E + 01
Methane, monochloro-, R-40	kg	1.30E + 01
Methane, tetrachloro-, R-10	kg	1.40E + 03
Methane, tetrafluoro-, R-14	kg	7.39E + 03
Methane, trichlorofluoro-, CFC-11	kg	4.75E + 03
Methane, trifluoro-, HFC-23	kg	1.48E + 04
Nitrogen fluoride	kg	1.72E + 04
Sulfur hexafluoride	kg	2.28E + 04

Table A8. Characterisation factors non-renewable cumulative energy demand.

Substance	Unit	Non-renewable energy resources, fossil	Non-renewable energy resources, nuclear	Non-renewable energy resources, primary forest
Coal, brown, in ground	kg	9.90		
Coal, hard, unspecified, in ground	kg	19.10		
Gas, mine, off-gas, process, coal mining	Nm3	39.80		
Gas, natural, in ground	Nm3	38.29		
Uranium, in ground	kg		560,000	
Oil, crude, in ground	kg	45.80		
Peat, in ground	kg	9.90		
Energy, gross calorific value, in biomass, primary forest	MJ			1.00

Table A9. Eco-Factors Ecological Scarcity 2006.

	Unit	Eco-factor expressed as eco-points
Emissions to air		
CO_2	g CO_2-eq	0.31
Ozone-depleting substances	R11-eq	11,000
NMVOC	G	18
NOx	G	45
NH3 (as N)	g N	70
SO_2	g SO_2-eq	30
PM2.5–10	g	150
PM2.5	g	150
Diesel soot	g	17,000
Benzene	g	3800
Dioxins and Furans	g	5.70E + 10
Lead	g	27,000
Cadmium	g	460,000
Mercury	g	210,000
Zinc	g	4400
Emissions to surface waters		
Nitrogen (as N)	g N	64
Phosphorus (as P)	g P	1200
COD	g	2.3
Arsenic	g	8000
Lead	g	4400
Cadmium	g	290,000
Chromium	g	7600
Copper	g	14,000
Nickel	g	6800
Mercury	g	880,000
Zinc	g	5000
Radioactive emissions	kBq C14-eq	1100
AOX (as Cl−)	g Cl	200
Chloroform	g	1500
PAHs	g	11,000
Benzo(a)pyrene	g	210,000
Endocrine disruptors	g E2-eq	8,700,000
Emissions to groundwater		
Nitrogen (as N)	g N	120
Emissions to soil		
Lead	g	31,000
Cadmium	g	310,000
Copper	g	13,000
Zinc	g	2800
Plant protection products	g PPP-eq	730
Resources		
Primary energy carriers	MJ-eq	3.3
Land use, settlement area	m^2a-eq	220
Freshwater Switzerland	m^3	22
Freshwater OECD	m^3	97
Gravel	g	0.029
Wastes		
C to landfill	g C	15
Hazardous wastes to underground repositories	g	27
High-level radioactive wastes	cm^3	18,000
Low/ medium-level radioactive wastes	cm^3	3300