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Assessment of carbon dioxide emissions during production, construction and use stages of asphalt pavements

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ABSTRACT

The carbon dioxide emissions generated during the life of flexible asphalt pavements are an important indicator of the sustainability of these infrastructures. The study aims at tentatively quantifying the CO_2 released during production, construction and use stages of a road pavement, the analysis is performed adopting a Life Cycle Assessment approach. Each stage is structured based on data retrieved from an extensive literature review. Special focus is given to the use stage, which is usually only partially addressed. The study is achieved employing the "HERMES CO_2" spreadsheet tool developed for the purpose and it is publicly available to maximize openness and the interaction with the user. As an illustrative application, the study then quantifies the generation of carbon dioxide for the three major categories of Norwegian highways referring to 1 km as functional unit with lifespan of 50 years. The analysis documents that the overall CO_2 amount is approximately equal to 1 million metric tons, which is significantly related to the albedo and rolling resistance of the use stage. Overall, the research establishes a common methodology and analysis frame which is relevant to early planning of road pavements and can be refined further for specific case-studies.

1. Introduction

1.1. Background

Pavement design and management decisions are commonly driven by technical, economic and safety aspects (Plati, 2019; Tarefder and Bateman, 2010). In recent years, in addition, more and more urban road and highway agencies have been increasingly interested in assessing the impacts of their decisions on the environment. Estimations of the carbon dioxide emissions generated during road life have already been requested during the tendering phase of some projects (Bryce et al., 2017; Huang et al., 2009b). Even if different practices may be used in each country, this gives unambiguous signal to the industry about the direction of the tendering criteria in the long run (Anthonissen et al., 2015).

The asphalt sector faces several challenges that are expected to intensify; i.e., costs and availability of construction materials, increase in traffic volume and loads, demands for longer-lasting pavements and use of recycled materials (Santero et al., 2011a; Tatari et al., 2012). Globally, the pavement infrastructure is composed of approximately 16.3 million kilometres and about 25 million kilometres of new roads are expected to be built by 2050 (Laurance et al., 2014; Plati, 2019). In Europe, the total production of Hot Mix Asphalt (HMA) and Warm Mix Asphalt (WMA) has been approximately equal to 300 million metric ton each year between 2008 and 2018 (EAPA, 2018). The amount of produced carbon dioxide CO_2 can be related to the sustainability of pavement infrastructures: evaluating the emissions generated during production, construction and use stages of a road life contributes to define the environmental burden. Worldwide, as environment and human beings are facing the brunt of pollution related to anthropogenic activities (Li et al., 2019; Lou et al., 2021a), several countries have reached a consensus on reducing CO_2 emissions and pollution levels in general with international environmental agreements (Marchiori et al.,

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Nomenclature

A	area
C	capacity of transport vehicle
e	Nepero's number
EF_{dsl}	emission factor diesel
f	lane distribution factor
FC	fuel consumption
FC_{tr}	fuel consumption associated to material transport
Ic	fuel consumption indicator
K	coefficient of fuel consumption difference between empty and full vehicle
LF	load factor
LF_1	load factor 1
LF_2	load factor 2
n	road lifespan
P	power
Pr	productivity
r	yearly traffic increase
R	mean distance travelled by transport vehicle
SC	specific consumption
t	time
α	albedo
δ	grade of slope
ρ	density
ρ_f	density of fuel
AADT	Annual Average Daily Traffic
AC	Asphalt Concrete
CDE	Carbon Dioxide Emission
CMH	Ceramic Metal Halide
DV	Diesel Vehicle
EM	Earthwork Machine
EOL	End-Of-Life
EV	Electric Vehicle
FCF	Fuel Consumption Factor
HMA	Hot Mix Asphalt
HV	Hybrid Vehicle
IRI	International Roughness Index
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LED	Light Emitting Diode
SL	Speed Limit

2017; Skelton, 2013; Wang, 2013). When it comes to the construction of transport infrastructures (Krantz et al., 2017; Liu et al., 2017), cross-country projects and consortia, such as "HERMES" (Anastasio et al., 2019; JPI Urban Europe Management Board, 2019), have been launched in order to promote awareness around the issue and develop critical thinking and solutions to ensure the sustainability of road pavements.

1.2. Pavement life cycle assessment and research objective

Life Cycle Assessment (LCA) is a technique originally developed to characterize the environmental impacts associated with industrial products. It comprises the "compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product throughout its life cycle" (CEN, 2006a; 2006b), intended as consecutive stages from material extraction to final disposal.

There are four phases in a LCA study 1) goal and scope definition 2) inventory analysis 3) impact assessment 4) interpretation. Unlike processes and services in other industries, LCA is still in the relatively early application in civil infrastructures (Inyim et al., 2016). The application of LCA to road pavements was initially performed in 1996 (Häkkinen and Mäkelä, 1996), 1998 (Horvath and Hendrickson, 1998) and 2001 (Stripple, 2001). The existing literature shows a significant heterogeneity in the parameters adopted to perform LCAs (i.e. functional unit) and the inconsistencies often prevent any international comparison attempt (Hoxha et al., 2021; Jiang and Wu, 2019; Wang et al., 2021). Therefore, all inputs (i.e. material resources) and outputs (CO_2 emissions) are normalized in this research to a common frame to harmonize the inventory data for apples-to-apples comparison.

The investigation encompasses production, construction and use stage of a road infrastructure; each stage is characterized based on the data retrieved from an extensive literature review. Life Cycle Inventory (LCI) is the central part of the LCA study and all the significant burdens (input and output) belonging to the road life are quantified and compiled. Special focus is given to the use stage, since this is usually partially addressed notwithstanding its tremendous importance (Araújo et al., 2014). The study has developed the "HERMES CO_2" spreadsheet tool to evaluate CO_2 emissions and it is publicly available (https://data.mendeley.com/datasets/xf5cvrkwps/3).

Compared to other existing tools (Dos Santos et al., 2017), "HERMES CO_2" maximizes openness and transparency of the analysis and the interaction allowed with the user. The current version of the spreadsheet implements a wide inventory database built from extensive literature review. On the other hand, the only environmental metric considered in this tool is the carbon dioxide CO_2 emission; anyway, this is a very relevant parameter to define pollution and one of the most detrimental to human health (Huijbregts et al., 2000a; Huijbregts et al., 2000b).

2. Methodological assessment

All the elements that are considered or not considered in this study are explicitly disclosed, according to the principles of reproducibility and comprehensiveness (Butt et al., 2015; Pennington et al., 2004; Rebitzer et al., 2004).

The evaluation of carbon dioxide emissions generated during the life of an asphalt pavement is accomplished with the analysis performed employing the developed "HERMES CO_2" spreadsheet. The intended audience is composed by road administrations, highway agencies and consultants. A process LCA approach is considered: compared to input/output (I/O) modelling (Leontief, 1970), a major effort for compiling "all" data of the product system is required (Rebitzer et al., 2004). Functional unit and system boundaries are the most important parameters that affect the results (Suh et al., 2004). The length of the road referred to as functional unit and its lifespan can be specified in the spreadsheet. Dimensions and materials for each road layer may vary, these are treated as variable quantities to be defined by the user. The analysis structure of "HERMES CO_2" spreadsheet is reported in Fig. 1: it includes twelve worksheets, each of them is identified by a 3- or 4-letter acronym.

Currently, there are four other major tools suitable to offer an indicative quantification of CO_2 emissions during the early planning of road infrastructures (Miliutenko et al., 2014), namely EFFEKT (NPRA, 2018a), JOULESAVE (Kennedy, 2006), KLIMATKALKYL (Toller, 2018) and LICCER (Potting et al., 2013). Comparing all the five models as reported in Table 1, "HERMES CO_2" also takes into consideration inputs that are seldom touched in a single tool by including use stage parameters such as lighting, albedo and rolling resistance (Santero and Horvath, 2009; Trupia et al., 2017; Wang et al., 2012). The ultimate fate of the pavement connected to the End-Of-Life (EOL) stage is difficult to determine; therefore, "HERMES CO_2" conservatively adopts a cutoff approach and assumes that the existing pavement does not receive any environmental benefits for its potential to produce recycled materials (Chong and Wang, 2017; Huang et al., 2013).

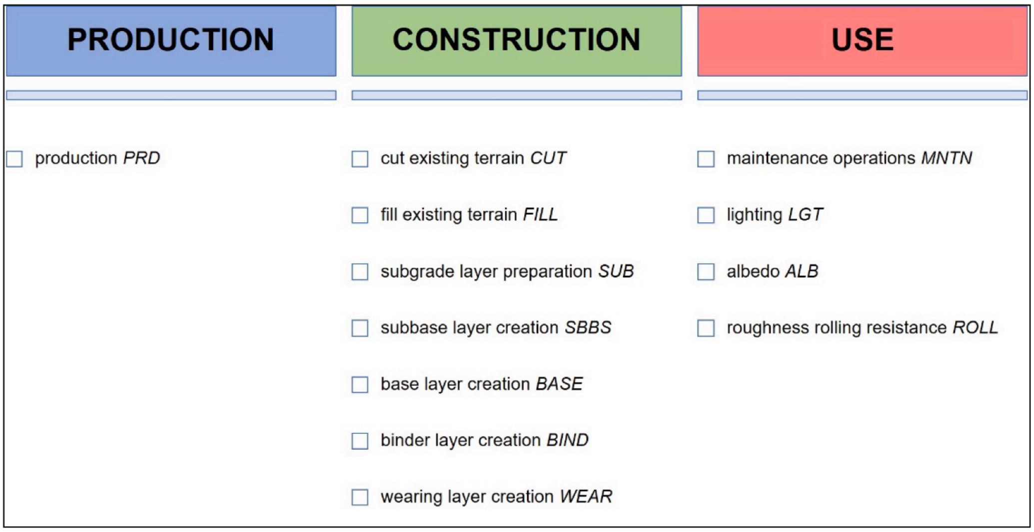

Fig. 1. Stages considered for the evaluation of CO_2 emissions:structure of the “HERMES CO_2” spreadsheet.

Table 1
Comparison between existing tools that indicatively quantify CO_2 emissions of road pavements.

Module Tool	PRD	CUT	FILL	SUB	SBBS	BASE	BIND	WEAR	MNTN	LGT	ALB	ROLL	EOL
HERMES CO_2	x	x	x	x	x	x	x	x	x	x	x	x	
EFFEKT	x	x	x	x	x	x	x	x	x	x			
JOULESAVE	x	x	x	x	x	x	x	x					
KLIMATKALKYL	x	x	x	x	x	x	x	x	x	x			
LICCER	x	x	x	x	x	x	x	x	x	x			x

2.1. Production stage

The production stage includes materials extraction and manufacture. For this purpose, a comprehensive literature review article has been referred to regarding Hot Mix Asphalt (HMA), gravel and sand (Thives and Ghisi, 2017). Natural gas and petroleum oil are combusted in plants, and they represent the main source of emissions. The kg CO_2 equiv./weight of HMA, gravel and sand are equal to 0.0238, 0.0027, 0.0023, respectively (Thives and Ghisi, 2017). The emissions associated with the production of fuels, process known as re-combustion, are not included.

2.2. Construction stage

There are several construction options that may need to be considered; therefore, the corresponding worksheets include a variety of inputs, i.e. dimensions and density of each layer. Moreover, it is possible to define the Earthwork Machines (EMs) according to different technical parameters. The worksheets CUT, FILL and SBGR are connected to creation of cut sections, creation of embankment sections and compression of subgrade, respectively; moreover, it is possible to take into consideration the presence of spreader and mixer applying potential stabilizing agents, which represents a relevant topic when it comes to create sustainable infrastructures (Barbieri et al., 2021b, 2020b; Jones, 2017) especially when strong rock materials are not locally available due to the given geology (Adomako et al., 2021). Up to five types of soil layers and three types of excavators, loaders and trucks can be defined as well as the respective properties. The SBBS, BASE, BIND and WEAR worksheets consider the construction of subbase, base, binder and wearing layers, respectively. Dozers, compactor rollers, asphalt paver, seal coat agent spreader and trucks are the machineries involved in these operations (Huang, 2004; Thom, 2014).

The carbon dioxide emissions generated by construction equipment are the main source of on-site environmental impact and they are mainly connected to the type of moved material, the inclination of terrain and the working time. Additional parameters not included in “HERMES CO_2”, such as altitude, humidity, temperature, maintenance and worker’s ability, may contribute to a more thorough description of the emissions (Fu et al., 2012). Over a hundred pieces of equipment have been considered and classified into main types based on 10 000 h to 14 000 h of working life expectancy for a diesel engine (Abolhasani et al., 2008; Frey et al., 2010; Trani et al., 2016). The surveyed machineries are dozers, excavators, loaders, compaction rollers, freighting vehicles and asphalt pavers (Fig. 2 and Fig. 3). The carbon dioxide emissions *CDE* related to the fuel consumption required to perform 1 m^3 of any activity can be obtained with (Heidari and Marr, 2015; Muresan et al., 2015; Trani et al., 2016)

$$CDE\left(\frac{kg}{m^3}\right) = FC\left(\frac{l}{m^3}\right)\bullet \mathrm{EF_{dsl}} \tag{1}$$

where *FC* is the fuel consumed and EF_{dsl} represents the emission factor for diesel, which is assumed to be 2.60 kg of CO_2 per litre. The fuel consumption *FC* of a given piece of equipment can be calculated as

$$FC\left(\frac{l}{m^3}\right) = P(kW)\bullet \mathrm{SC}\left(\frac{\mathrm{kg}}{\mathrm{kWh}}\right)\bullet \mathrm{LF}\bullet\frac{1}{\rho_f\left(\frac{\mathrm{kg}}{\mathrm{l}}\right)}\bullet \mathrm{Pr}\left(\frac{\mathrm{h}}{\mathrm{m}^3}\right) \tag{2}$$

where *P* represents the power, *SC* is the specific consumption and depends on the engine’s characteristic curve, *LF* stands for the load factor and refers to the instantaneous loading of the engine in relation to its maximum capacity (expressed as a percentage), ρ_f denotes the density of the fuel, assumed to be 0.85 kg/l, and *Pr* represents the productivity. *LF* can be expressed as a combination of two load factors LF_1 and LF_2 as

$$LF = \frac{LF_1 + LF_2}{2} \tag{3}$$

the parameters LF_1 and LF_2 vary according to the considered piece of equipment as reported in Table 2. LF_1 and LF_2 are related to the soil

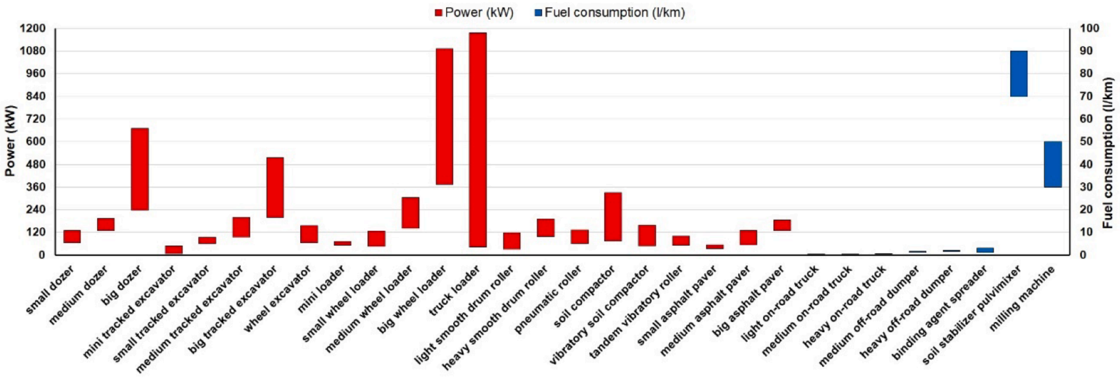

Fig. 2. Power and fuel consumption of the construction equipment (Celauro et al., 2015; Trani et al., 2016).

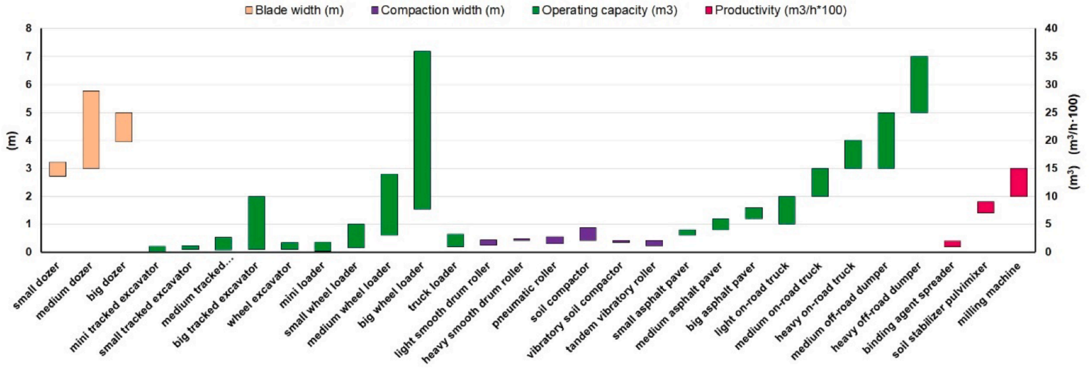

Fig. 3. Operating width, operating capacity and productivity of the construction equipment (Celauro et al., 2015; Trani et al., 2016).

Table 2
Load factors LF_1 and LF_2 for construction equipment (Caterpillar, 2017; Komatsu, 2009).

Equipment	LF_1 (–)	LF_2 (–)
excavator	$0.0339e^{0.0014\rho}$	$0.2007e^{0.0262t}$
loader, paver	$0.05862e^{0.00101\rho}$	$0.00868\delta + 0.15333$
roller compactor	$0.05173e^{0.00142\rho}$	$0.21032\delta^{0.43210}$

density ρ, the duration of the daily work schedule t expressed in minutes, the density in bank and density loose of the soil and the grade of the slope δ, which varies between 0° and 35° for geomaterials (Frey et al., 2010; Trani et al., 2016). Fig. 4 reports different types of soil with density in bank and density loose. The fuel consumed by trucks and dumpers FC_{tr} in the transport can be calculated as follows

$$\frac{FC_{tr}\left(\frac{l}{m^3}\right) = K \bullet R(km) \bullet Ic\left(\frac{l}{km}\right)}{C(m^3)} \tag{4}$$

where K is the coefficient of the difference between the fuel consumption of an empty truck and a fully loaded one ($K = 1.7$), R is the mean

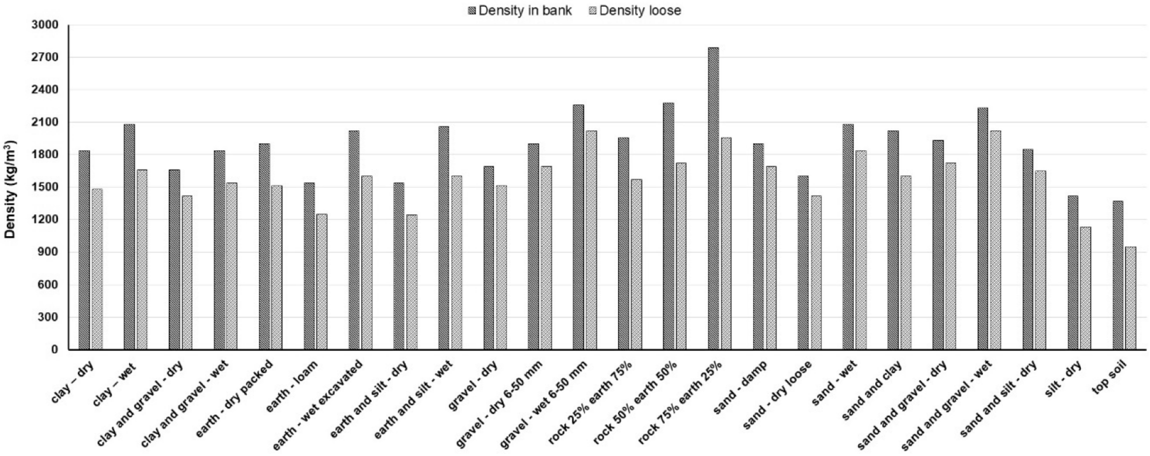

Fig. 4. Density characterization of soils (Celauro et al., 2015).

distance travelled, *Ic* represents the fuel consumption indicator of the fully loaded truck and *C* is the capacity of the vehicle. Generally, reducing the travelled distance *R* by adopting materials that are locally available is an effective approach to reduce the pollutant emissions (Barbieri et al., 2021a; Barbieri et al., 2019a). Fuel consumptions of binding agent spreader, soil stabilizer pulvimixer and milling machine are also assessed according to Equation (4) based on the values reported in Fig. 2 (Celauro et al., 2015).

2.3. Use stage

The use stage is typically ignored in existing studies due to its inner complexity, thus probably representing "the most significant shortfall from a system boundary perspective" (Santero et al., 2011b). The road use stage has an enormous supremacy with respect to energy consumption and gaseous emissions: the majority of such environmental loadings mainly come from the traffic vehicles during the life time (Araújo et al., 2014; Galatioto et al., 2015; Huang et al., 2009b; Inti et al., 2016). In the following subsections, the pavement-vehicle interaction is only considered in terms of roughness and not deflection nor texture since no findings universally agreed upon in the research community have been reached so far (Santero et al., 2011c; Xu et al., 2019). Moreover, it is important to highlight that the leachate generated from road pavements is not contemplated as previous research studies have reported a small amount of leaching of contaminants (Brandt and De Groot, 2001; Marion et al., 2005). Therefore, considering that "HERMES CO_2" is mainly relevant to early planning of road pavements, the inclusion of leachate is not likely to remarkably affect the overall results.

2.3.1. Maintenance

Maintenance operations refer to the creation of asphalt overlays (Huang et al., 2009a; Zhang et al., 2010) when the International Roughness Index (IRI) of the pavement becomes unacceptable. IRI is defined by the amplitude of motion of a standard vehicle suspension system as it travels along the road (Múčka, 2017; Paterson, 1986). The initial IRI_{ini} of the new pavement can be specified in "HERMES CO_2". The yearly increase in IRI can be also defined and this value ΔIRI is recommended to be comprised between 0.05 m/km and 0.15 m/km (Albuquerque and Núñez, 2011; Xu et al., 2019; Yu and Lu, 2012). When IRI reaches the specified maximum threshold value IRI_{fin}, maintenance operations are performed and IRI value is re-set to its initial value IRI_{ini} (Bryce et al., 2014; Wang et al., 2020). An alternative approach to evaluate the need for road maintenance could also be developed based on rutting depth (Gulfam-E-Jannat et al., 2016).

2.3.2. Lighting

The two most common streetlight technologies are taken into consideration: one is based on Ceramic Metal Halide (CMH), one is based on Light Emitting Diode (LED) (Abdul Hadi et al., 2013). It is assumed that both CMH and LED bulbs are characterized by 60 000 h of operational life and that the electricity is supplied from a natural gas power plant. The hourly carbon dioxide emissions during operation of CMH-250 W and LED-180 W streetlights are 0.057 kg/h and 0.041 kg/h, respectively (Abdul Hadi et al., 2013).

2.3.3. Albedo

The albedo effect is the phenomenon related to the ratio of reflected radiation, which can be converted to a corresponding amount of CO_2. Albedo ranges from 0 (complete absorption) to 1 (complete reflectance). As a surface covering, pavements can reflect a portion of the incoming solar radiation back into space. Pavement age and surface type are the most important parameters to be considered (Yu and Lu, 2014). The albedo of asphalt pavements increases with age as the road surface becomes clearer, in contrast with the concrete pavements, which are likely to darken with time. The fundamental function describing the relationship of solar radiative force *RF* and carbon dioxide emission CO_2 is given as (Yu and Lu, 2014)

$$\frac{CO_2(kg) = \frac{\alpha}{0.01}\cdot 1.087\bullet RF\left(\frac{W}{m^2}\right)\bullet t\bullet A(m^2)}{0.217\bullet t - 44.78\bullet \mathrm{e}^{-\frac{t}{172.9}} - 6.26\bullet \mathrm{e}^{-\frac{t}{18.51}} - 0.22\bullet \mathrm{e}^{-\frac{t}{1.186}} + 51.26} \tag{5}$$

where α is the albedo value, *t* is time expressed in years and *A* is the area. Albedo is connected to latitude coordinate, vegetation and cloud cover (Myhre and Myhre, 2003); for simplification, national codes typically assume a single, static value of albedo over the service life (Sen and Roesler, 2016). "HERMES CO_2" does not explicitly take into account the urban heat island effect, but this phenomenon can be indicatively estimated by selecting an appropriate value of α and radiative force *RF* (Akbari et al., 2001; Qin, 2015).

2.3.4. Rolling resistance

The rolling resistance describes the energy loss of the moving vehicles associated to the surface properties of the pavement and can be efficiently correlated to IRI (Santero et al., 2011c; Wang et al., 2012; Yuan et al., 2015). It is important to emphasize that the rolling resistance investigated here does not refer to the entire burden of fuel use, but rather just to the effect of pavement properties on the fuel economy of vehicle (Andre, 2005; Kim et al., 2015). Moreover, the impact of road texture on fuel consumption is not straightforward, the relationship heavily depends on engine rate; at low speed the mechanical friction is predominant, at higher speed the aerodynamic resistance plays a major role (Lepert and Brillet, 2009). Given the very limited number of studies that consider the effect of pavement roughness, its role is often approximated by linear or exponential models (Azarijafari et al., 2016; Inyim et al., 2016; Zhang et al., 2010). Fuel Consumption Factor *FCF* is used to describe the additional fuel consumption of vehicles according to different IRIs (Yu and Lu, 2012)

$$\mathrm{FCF} = 0.007377\cdot\mathrm{IRI} + 0.993 \tag{6}$$

$$\mathrm{FCF} = 0.02163\cdot\mathrm{IRI} + 0.953 \tag{7}$$

where Equation (6) is for passenger cars, and Equation (7) is for trucks ($FCF \geq 1$).

The diesel fuel consumption for road trucks and light vehicles (Diesel Vehicles, DVs) is assumed to be 0.25 l/km (Trani et al., 2016) and 0.06 l/km (Lopes et al., 2013), respectively. It is important to highlight that the worksheet also considers the possible presence of light Hybrid Vehicles (HVs) as well as light Electric Vehicles (EVs). The consumption of HVs is set to 0.04 l/km (Fontaras et al., 2008). In order to merely consider the amount of CO_2 related to driving, no direct emissions are associated with EVs (Hawkins et al., 2012; Richardson, 2013).

To forecast the Annual Average Daily Traffic (AADT) at a given year, the formulation implemented in "HERMES CO_2" is

$$AADT(t) = AADT(1)\cdot f\bullet\frac{(1+0.01\bullet \mathrm{r})^{\mathrm{n}} - 1}{0.01\bullet \mathrm{r}} \tag{8}$$

where AADT(1) refers to the initial value, *r* is the yearly traffic increase, *n* is the road lifespan and *f* is the lane distribution factor, which is equal to 1.00, 0.50, 0.45 or 0.40 for one-lane, two-lane, four-lane and six-lane road, respectively (Fwa and Li, 1995; Mallick and El-Korchi, 2013; Šliupas, 2006). The amount of diesel heavy, diesel light, hybrid and electric vehicles is specified by the spreadsheet user as four respective AADT values.

3. Application of "HERMES CO_2" tool

3.1. Functional unit and system boundary

As illustrated in section 2, the "HERMES CO_2" tool is developed based on an extensive literature review and, therefore, it can be applied to a wide range of various road projects in different locations. In this work, “HERMES CO_2” is employed considering the context of Norwegian road pavements. The goal of this application is to indicatively evaluate the carbon dioxide emissions generated during the life of a typical Asphalt Concrete (AC) highway pavement (NPRA, 2018b) and highlight the most pollutant stages.

In this regard, the three layouts of road pavement corresponding to the three dimensioning classes of Norwegian highways are taken into consideration (NPRA, 2019). They are classified as H1, H5 and H3 based on their Annual Average Daily Traffic (AADT) and Speed Limit (SL): $\mathrm{AADT}_{H1} < 6\,000 < \mathrm{AADT}_{H5} < 12\,000 < \mathrm{AADT}_{H3}$ and $\mathrm{SL}_{H1} = 80$ km/h, $\mathrm{SL}_{H5} = 90$ km/h, $\mathrm{SL}_{H3} = 110$ km/h. Fig. 5 depicts the three layouts of the highway classes H1, H5 and H3 as well as three examples of corresponding road pavements located along highways E39 Lyngdal-Flekkefjord (Barbieri et al., 2017), E6 Trondheim-Stjørdal (Hanson, 2012) and E16 Bærum-Sandvika (Mijena, 2019).

This application refers to 1 km as functional unit and 50 years as lifespan. The materials and the geometry of the considered road pavements are reported in Table 3, they are typical values in the Norwegian context (NPRA, 2019, 2018b). The subgrade is composed of rocks and is non-frost susceptible. The base and subbase layers comprise gravel which is spread and compacted by means of medium dozer and light smooth drum roller, respectively. The binder and wearing courses are created using medium asphalt paver, tandem vibratory roller, tack coat spreader and seal coat spreader. The transport distance for all the materials included in the study is assumed to be 20 km, this is a reasonable estimation as using local materials has proved to be a good practice to limit the generation of CO_2 in the country (Barbieri et al., 2020a, 2019b).

The lighting poles are assumed to function 12 h a day throughout the year using LED bulbs, and the distance between two poles is set to 50 m. Regarding the roughness of the pavement, the following values are adopted: $\mathrm{IRI}_{ini} = 2$ m/km, $\Delta\mathrm{IRI} = 0.10$ m/km and $\mathrm{IRI}_{fin} = 4$ m/km (NPRA, 2014a, 2014b). In this study, maintenance operations comprise the removal of the existing top layer (wearing + binder) and its reconstruction. The following machineries are used: milling machine, compactor rollers, asphalt paver, seal coat agent spreader and trucks. As in the case of the initial road construction, the material transport distance is assumed to be 20 km.

Table 3
Materials and geometry of the analysed road pavements.

Layer	Material	Thickness (cm)	Width (m)		
			H1	H5	H3
wearing	AC	4	9	12.5	23
binder	AC	4	9	12.5	23
base	gravel	30	9	12.5	23
subbase	gravel	30	12	15.5	26
subgrade	rock	–	15	18.5	29

When it comes to the albedo, this study adopts a constant static value of $\alpha = 0.15$; this is a conservative estimate, since fresh asphalt is generally characterised by $\alpha = 0.05$–0.10. Anyway, the variability in α is significant only during the first or two years after road construction (Richard et al., 2015; Sen and Roesler, 2016). Pavements generally have lower albedos than their surrounding areas. Dobos assessed the albedo values for several types of surfaces and documented that the mean value of the earth system is 0.36 (Dobos, 2014). Therefore, in this study, the difference between asphalt pavement and the surrounding area is $\Delta\alpha = 0.21$. Mean *RF* value is assumed to be 1.54 W/m^2 for 0.01 change in albedo (Yu and Lu, 2014).

The AADT referring to light vehicles AADT_{light} as well as the values of lane distribution factors f are reported in Table 4 (NPRA, 2020), the yearly increase in traffic is $r = 1\%$ (NPRA, 2018b). The AADT referring to heavy vehicles AADT_{heavy} is considered to be 5% of AADT_{light} (Statistics Norway, 2021). Initially, only the presence of DVs is considered.

Table 4
Estimated values of AADT_{light} and lane distribution factor f for each highway dimensioning class.

Highway dimensioning class	H1	H5	H3
AADT_{light}	6 000	12 000	20 000
f	0.50	0.50	0.45

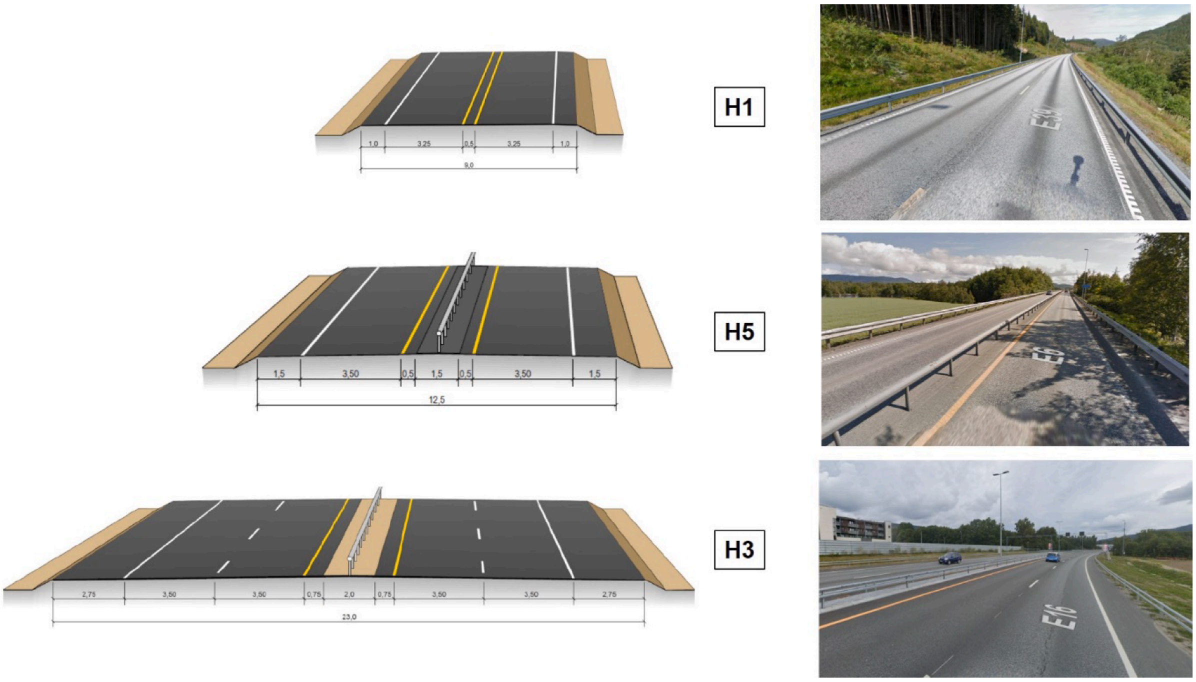

Fig. 5. The three dimensioning classes of Norwegian highways, dimensions in m (Google Maps, 2021; NPRA, 2019).

3.2. Results and discussion

The carbon dioxide emissions related to the production, construction and use stages for the analysed highway pavements are reported in Fig. 6a in logarithmic scale. The overall amount of generated CO_2 is comprised between three hundred thousand and one million metric tons. It is apparent that production stage and construction stage are characterized by the same order of magnitude (100 t) as better depicted in Fig. 6b and are noticeably connected to a tiny portion of the total amount. On the other hand, the use stage, which is seldom touched in literature, contributes tremendously to the overall emissions (more than 99%) and this finding is in good agreement with previous studies (Araújo et al., 2014; Santero et al., 2011c). In this regard, Fig. 6c details the impact of all the modules comprised in the use stage. The lighting module is characterized by the same order of magnitude of the production stage or the construction stage, while albedo and rolling resistance modules heavily impact the results as they determine more than 99% of the emissions related to the use stage. Fig. 6d reports that the light vehicles and heavy vehicles are responsible for approximately 85% and 15% of the emissions, respectively, related to the rolling resistance module.

Considering that the very large part of the carbon dioxide emissions is actually related to albedo and rolling resistance, some further considerations are made referring to the dimensioning class H3 by performing a parametric analysis which involves “ALB” and “ROLL” worksheets. Fig. 7 depicts the role played by albedo α and radiative force *RF* and indicates that a careful evaluation of these two parameters is essential to obtain a precise estimate of the generated amount of CO_2. The results show that, even if there is a sensible variation in the emissions quantity, the order of magnitude is the same (10 000 t) for all the considered values of α (0.05, 0.08, 0.10, 0.13, 0.15) and *RF* (1.00, 1.25, 1.50, 1.75, 2.00 W/m^2), which is in good agreement with previous research (Sen and Roesler, 2016).

The emissions related to the rolling resistance represent the largest

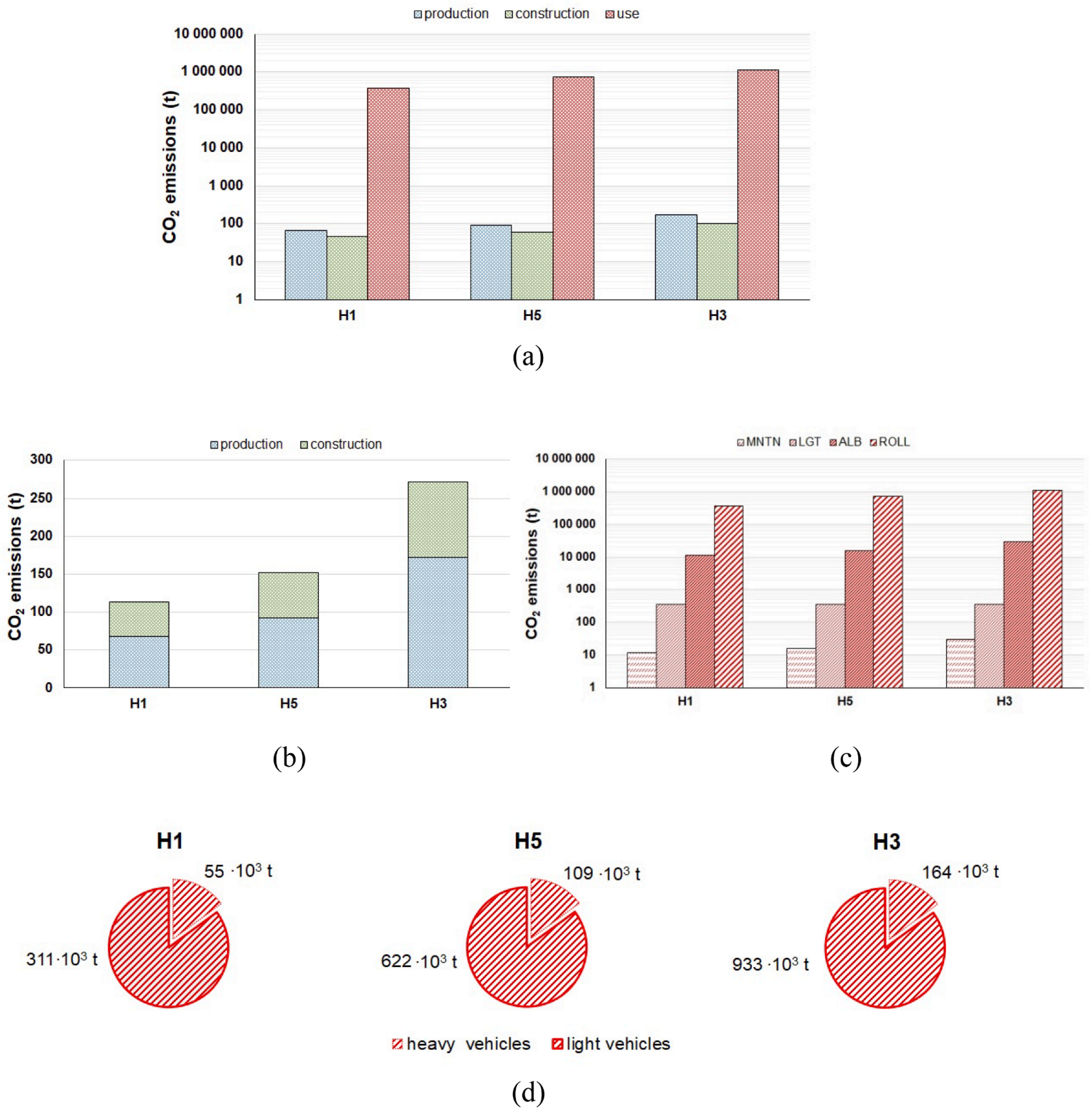

Fig. 6. Quantity of generated CO_2 emissions related to all the stages (a), related to production and construction stages (b), related to use stage with subdivision between maintenance, lighting, albedo and rolling resistance modules (c) and related to rolling resistance module with subdivision between heavy and light vehicles (d). Results evaluated for each highway dimensioning class H1, H5 and H3.

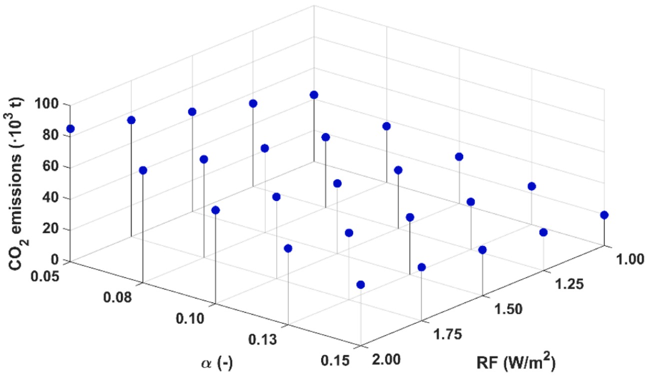

Fig. 7. Influence of albedo α and radiative force *RF* on CO_2 emissions.

part of the overall amount; therefore, it is relevant to understand how this outcome can change when also taking the presence of HVs and EVs into consideration. With particular reference to the Norwegian context, sustainability is a key-value for all the societal sectors (NPRA, 2018c; Samferdselsdepartementet, 2018; Teknologirådet, 2012) and, when it comes to transport, the country's ambitious policy to reach carbon neutrality in the very near future largely relies on the growing electric vehicle market (Ćetković and Skjærseth, 2019; Sovacool et al., 2018). Fig. 8 displays along the horizontal axes the quantity of HVs and EVs expressed as a percentage (0.00, 0.25, 0.50, 0.75, 1.00) of the total $AADT_{light}$ including light DVs, HVs and EVs. Three values of traffic volume ($AADT_{light}$ = 10 000, $AADT_{light}$ = 20 000, $AADT_{light}$ = 30 000) and three values of yearly increase in roughness ($\Delta IRI = 0.05$, $\Delta IRI = 0.10$, $\Delta IRI = 0.15$) are considered. A linear relationship is found between the amount of generated CO_2 and the percentage of DVs, HVs, EVs. In example, the carbon dioxide quantity associated to $AADT_{light}$ composed by 100% DVs is halved when referring to an $AADT_{light}$ comprising 50% DVs and 50% EVs or reduced by 17% when referring to an $AADT_{light}$ encompassing 50% DVs and 50% HVs. Therefore, the presence of HVs and EVs proves to be a very effective way to reduce the amount of emissions generated by rolling resistance. As an input for a future upgrade of the "HERMES CO_2" tool, it is worth mentioning that further benefits in terms of reduction of CO_2 emissions can be achieved when considering electric trucks (Liimatainen et al., 2019). Fig. 8 also depicts the emissions connected to two different acceptable maximum IRI ($IRI_{fin} = 3$, $IRI_{fin} = 4$) entailing two different frequencies of maintenance operations; in this case, no significant variations in the CO_2 emissions are found and this agrees well with other studies (Kim et al., 2015; Zhang et al., 2010).

4. Limitations and conclusions

The study has dealt with the indicative assessment of carbon dioxide emissions connected to the life of an asphalt pavement considering its production, construction and use stages. "HERMES CO_2" tool is a publicly available spreadsheet which has been developed for the purpose and its structure is based on data gathered from an extensive literature review. Considering the several LCA tools that are currently available in the road sector, just a few are designed to perform considerations at early phases. In particular, "HERMES CO_2" gives focus to the use stage, which is usually only partially addressed in the other tools relevant to early planning of road pavements. As "HERMES CO_2" can be applied to various road projects located in different places and countries, this study has indicatively calculated the CO_2 emissions related to the life of three types of Norwegian highway pavements to illustrate the potential of the developed tool.

The fact that all the data employed in this study have been derived from previous investigations represents a natural limitation; hence, the quantitative results obtained here should be considered indicative only and highlight the most critical stages in terms of CO_2 generation. Moreover, specific testing campaigns to measure accurately the values of relevant parameters such as albedo or rolling resistance should be performed associated with a specific case-study.

Notwithstanding these limitations, three major conclusions can be drawn:

(1) "HERMES CO2" is an effective tool which can indicatively assess the CO_2 emissions related to the life of an asphalt pavement.

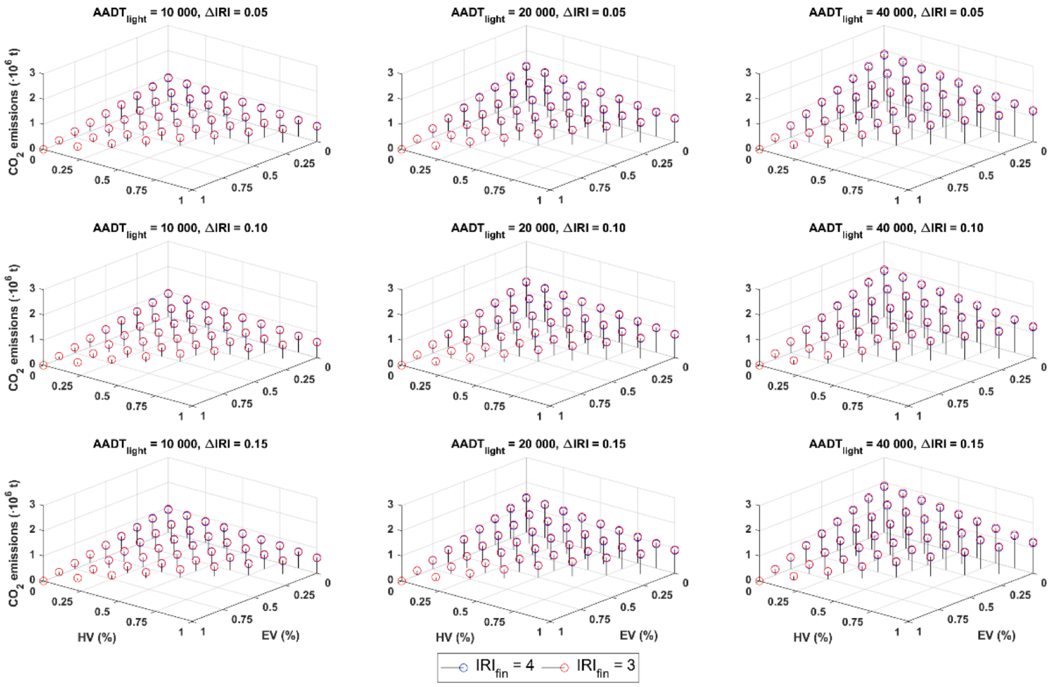

Fig. 8. Influence of the presence of Hybrid Vehicles (HVs) and Electric Vehicles (EVs) on CO_2 emissions related to rolling resistance, results displayed for two different road maintenance frequencies ($IRI_{fin} = 3$, $IRI_{fin} = 4$).

"HERMES CO_2" is particularly relevant to early planning of road infrastructures and, differently from the other existing tools, also considers the use stage.

(2) Based on the illustrative application of "HERMES CO_2" to the calculation of CO_2 emissions related to Norwegian highways, it is possible to infer that the use stage is associated to tremendous emissions and that the albedo effect and the rolling resistance are the main responsible.

(3) The rolling resistance plays a predominant role in the generation of carbon dioxide emissions because it affects each vehicle using the pavement. The presence of Hybrid Vehicles (HVs) and Electric Vehicles (EVs) can significantly reduce these emissions.

As recommendations for future research, the development of "HERMES CO_2" tool should target the following objectives: (i) more accurate quantification of the phenomena generating tremendous but vague amount of environmental burdens (i.e., albedo, rolling resistance and pavement-vehicle interaction), (ii) consideration of uncertainties for the input quantities, which can be in turn incorporated in Monte Carlo simulations (Yu et al., 2018), (iii) dynamic representations of data and creation of a temporal Life Cycle Inventory (LCI) (Azarijafari et al., 2016; Pinsonnault et al., 2014), (iv) inclusion of the most recent technologies currently in experimental phase, i.e. self-healing asphalt mastic (Liu et al., 2013; Lou et al., 2021b; Lou et al., 2021c), energy harvesting (Guo and Lu, 2017; Roshani et al., 2016) and electric road systems (Jelica et al., 2018; Taljegård et al., 2019).

CRediT authorship contribution statement

Diego Maria Barbieri: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Resources, Data curation, Writing – original draft. **Baowen Lou:** Methodology, Software, Validation, Formal analysis, Investigation, Resources, Data curation, Writing – original draft. **Fusong Wang:** Methodology, Software, Validation, Formal analysis, Investigation, Resources, Data curation, Writing – original draft. **Inge Hoff:** Methodology, Writing - review & editing, Visualization, Supervision, Project administration, Funding acquisition. **Shaopeng Wu:** Methodology, Writing - review & editing, Visualization, Supervision, Project administration, Funding acquisition. **Jiashuo Li:** Methodology, Writing - review & editing, Project administration, Funding acquisition. **Hrefna Run Vignisdottir:** Methodology, Writing - review & editing. **Rolf André Bohne:** Methodology, Writing - review & editing, Project administration, Funding acquisition. **Sara Anastasio:** Methodology, Writing - review & editing, Project administration, Funding acquisition. **Terje Kristensen:** Methodology, Writing - review & editing, Supervision, Project administration, Funding acquisition.

Declaration of Competing Interest

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

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References

Abdul Hadi, S., Al Kaabi, M.R., Al Ali, M.O., Arafat, H.A., 2013. Comparative Life Cycle Assessment (LCA) of streetlight technologies for minor roads in united arab emirates. Energy Sustain. Dev. 17, 438–450. https://doi.org/10.1016/j.esd.2013.05.001.

Abolhasani, S., Frey, H.C., Kim, K., Rasdorf, W., Lewis, P., Pang, S.H., 2008. Real-world in-use activity, fuel use, and emissions for nonroad construction vehicles: a case study for excavators. J. Air Waste Manag. Assoc. 58, 1033–1046. https://doi.org/10.3155/1047-3289.58.8.1033.

Adomako, S., Engelsen, C.J., Thorstensen, R.T., Barbieri, D.M., 2021. Review of the relationship between aggregates geology and Los Angeles and micro-Deval tests. Bull. Eng. Geol. Environ. https://doi.org/10.1007/s10064-020-02097-y.

Akbari, H., Pomerantz, M., Taha, H., 2001. Cool surfaces and shade trees to reduce energy use and improve air quality in urban areas. Sol. Energy 70, 295–310. https://doi.org/10.1016/S0038-092X(00)00089-X.

Albuquerque, F.S., Núñez, W.P., 2011. Development of roughness prediction models for low-volume road networks in northeast Brazil 198–205. https://doi.org/10.3141/2205-25.

Anastasio, S., Wu, S., Bohne, R.A., Passer, A., Spaun, S., Kristensen, T., Li, J., Xie, J., Kreiner, H., Hoff, I., Barbieri, D.M., Vignisdottir, H.R., Lau, A., Amirkhanian, S., 2019. Integrated evaluation of energy and emission reduction potential and management strategies for urban road systems, in: Sustainable Built Environment. Graz.

Andre, J.-M., 2005. Vehicle emission measurement collection of the Artemis database. Artemis 3312 Report.

Anthonissen, J., Van Troyen, D., Braet, J., Van Den Bergh, W., 2015. Using carbon dioxide emissions as a criterion to award road construction projects: a pilot case in Flanders. J. Clean. Prod. 102, 96–102. https://doi.org/10.1016/j.jclepro.2015.04.020.

Araújo, J.P.C., Oliveira, J.R.M., Silva, H.M.R.D., 2014. The importance of the use phase on the LCA of environmentally friendly solutions for asphalt road pavements. Transp. Res. Part D Transp. Environ. 32, 97–110. https://doi.org/10.1016/j.trd.2014.07.006.

Azarijafari, H., Yahia, A., Ben Amor, M., 2016. Life cycle assessment of pavements: Reviewing research challenges and opportunities. J. Clean. Prod. 112, 2187–2197. https://doi.org/10.1016/j.jclepro.2015.09.080.

Barbieri, D.M., Dorval, J.-G., Lou, B., Chen, H., Shu, B., Wang, F., Hoff, I., 2021a. Dataset regarding the mechanical characterization of sedimentary rocks derived from Svalbard for possible use in local road constructions. Data Br. 34, 106735 https://doi.org/10.1016/j.dib.2021.106735.

Barbieri, D.M., Hoff, I., Ho, C.-H., 2021b. Crushed rocks stabilized with organosilane and lignosulfonate in pavement unbound layers: Repeated load triaxial tests. Front. Struct. Civ, Eng https://doi.org/10.1007/s11709-021-0700-5.

Barbieri, D.M., Hoff, I., Mork, H., 2017. Laboratory investigation on unbound materials used in a highway with premature damage. in: 10th International Conference on the Bearing Capacity of Roads, Railways and Airfields.

Barbieri, D.M., Hoff, I., Mørk, M.B.E., 2020a. Organosilane and lignosulfonate as innovative stabilization techniques for crushed rocks used in road unbound layers. Transp. Geotech. 22 https://doi.org/10.1016/j.trgeo.2019.100308.

Barbieri, D.M., Hoff, I., Mørk, M.B.E., 2019a. Mechanical assessment of crushed rocks derived from tunnelling operations. In: Cheng, W.-.-C., Yang, J., Wang, J. (Eds.), 5th GeoChina International Conference 2018. Springer, pp. 225–241 https://doi.org/10.1007/978-3-319-95783-8_19.

Barbieri, D.M., Hoff, I., Mørk, M.B.E., 2019b. Innovative stabilization techniques for weak crushed rocks used in road unbound layers: a laboratory investigation. Transp. Geotech. 18, 132–141. https://doi.org/10.1016/j.trgeo.2018.12.002.

Barbieri, D.M., Tangerås, M., Kassa, E., Hoff, I., Liu, Z., Wang, F., 2020b. Railway ballast stabilising agents: Comparison of mechanical properties. Constr. Build. Mater. 252 https://doi.org/10.1016/j.conbuildmat.2020.119041.

Brandt, H.C.A., De Groot, P.C., 2001. Aqueous leaching of polycyclic aromatic hydrocarbons from bitumen and asphalt. Water Res. 35, 4200–4207. https://doi.org/10.1016/S0043-1354(01)00216-0.

Bryce, J., Brodie, S., Parry, T., Lo Presti, D., 2017. A systematic assessment of road pavement sustainability through a review of rating tools. Resour. Conserv. Recycl. 120, 108–118. https://doi.org/10.1016/j.resconrec.2016.11.002.

Bryce, J.M., Flintsch, G., Hall, R.P., 2014. A multi criteria decision analysis technique for including environmental impacts in sustainable infrastructure management business practices. Transp. Res. Part D Transp. Environ. 32, 435–445. https://doi.org/10.1016/j.trd.2014.08.019.

Butt, A.A., Toller, S., Birgisson, B., 2015. Life cycle assessment for the green procurement of roads: a way forward. J. Clean. Prod. 90, 163–170. https://doi.org/10.1016/j.jclepro.2014.11.068.

Caterpillar, 2017. Caterpillar Performance Handbook. Peoria.

Celauro, C., Corriere, F., Guerrieri, M., Lo Casto, B., 2015. Environmentally appraising different pavement and construction scenarios: a comparative analysis for a typical local road. Transp. Res. Part D Transp. Environ. 34, 41–51. https://doi.org/10.1016/j.trd.2014.10.001.

CEN, 2006a. ISO 14040 Environmental management - Life cycle assessment -. Principles and framework, Belgium.

CEN, 2006b. ISO 14044 Environmental management - Life cycle assessment - Requirements and guidelines. Belgium.

Ćetković, S., Skjærseth, J.B., 2019. Creative and disruptive elements in Norwaýs climate policy mix: the small-state perspective. Env. Polit. 28, 1039–1060. https://doi.org/10.1080/09644016.2019.1625145.

Chong, D., Wang, Y., 2017. Impacts of flexible pavement design and management decisions on life cycle energy consumption and carbon footprint. Int. J. Life Cycle Assess. 22, 952–971. https://doi.org/10.1007/s11367-016-1202-x.

Dobos, E., 2014. Albedo, in: Wang, Y. (Ed.), Encyclopedia of Natural Resources - Land - Volume I. CRC Press, p. 652. https://doi.org/https://doi.org/10.1201/9780203757628.

Dos Santos, J.M.O., Thyagarajan, S., Keijzer, E., Flores, R.F., Flintsch, G., 2017. Comparison of life-cycle assessment tools for road pavement infrastructure. Transp. Res. Rec. 2646, 28–38. https://doi.org/10.3141/2646-04.

EAPA, 2018. Asphalt in figures 2018. Brussels.

Fontaras, G., Pistikopoulos, P., Samaras, Z., 2008. Experimental evaluation of hybrid vehicle fuel economy and pollutant emissions over real-world simulation driving cycles. Atmos. Environ. 42, 4023–4035. https://doi.org/10.1016/j.atmosenv.2008.01.053.

Frey, H.C., Rasdorf, W., Lewis, P., 2010. Comprehensive field study of fuel use and emissions of nonroad diesel construction equipment. Transp. Res. Rec. 69–76 https://doi.org/10.3141/2158-09.

Fu, M., Ge, Y., Tan, J., Zeng, T., Liang, B., 2012. Characteristics of typical non-road machinery emissions in China by using portable emission measurement system. Sci. Total Environ. 437, 255–261. https://doi.org/10.1016/j.scitotenv.2012.07.095.

Fwa, T.F., Li, S., 1995. Estimation of lane distribution of truck traffic for pavement design. J. Transp. Eng. 121, 241–248. https://doi.org/10.1061/(ASCE)0733-947X(1995)121:3(241).

Galatioto, F., Huang, Y., Parry, T., Bird, R., Bell, M., 2015. Traffic modelling in system boundary expansion of road pavement life cycle assessment. Transp. Res. Part D 36, 65–75. https://doi.org/10.1016/j.trd.2015.02.007.

Google Maps, 2021. Google Maps [WWW Document]. URL https://www.google.com/maps/.

Gulfam-E-Jannat, Yuan, X.X., Shehata, M., 2016. Development of regression equations for local calibration of rutting and IRI as predicted by the MEPDG models for flexible pavements using Ontario's long-term PMS data. Int. J. Pavement Eng. 17, 166–175. https://doi.org/10.1080/10298436.2014.973024.

Guo, L., Lu, Q., 2017. Potentials of piezoelectric and thermoelectric technologies for harvesting energy from pavements. Renew. Sustain. Energy Rev. 72, 761–773. https://doi.org/10.1016/j.rser.2017.01.090.

Häkkinen, T., Mäkelä, K., 1996. Environmental adaption of concrete: Environmental impact of concrete and asphalt pavements. Espoo.

Hanson, S., 2012. Kalksementstabilisering ved E6 Trondheim – Stjørdal, parsell Trondheim dagsone vest. Norwegian University of Science and Technology.

Hawkins, T.R., Gausen, O.M., Strømman, A.H., 2012. Environmental impacts of hybrid and electric vehicles—a review. Int. J. Life Cycle Assess. 17, 997–1014. https://doi.org/10.1007/s11367-012-0440-9.

Heidari, B., Marr, L.C., 2015. Real-time emissions from construction equipment compared with model predictions. J. Air Waste Manag. Assoc. 65, 115–125. https://doi.org/10.1080/10962247.2014.978485.

Horvath, A., Hendrickson, C., 1998. Comparison of environmental implications of asphalt and steel-reinforced concrete pavements. Transp. Res. Rec. J. Transp. Res. Board 1626, 105–113. https://doi.org/10.3141/1626-13.

Hoxha, E., Vignisdottir, H.R., Barbieri, D.M., Wang, F., Bohne, R.A., Kristensen, T., Passer, A., 2021. Life cycle assessment of roads: Exploring research trends and harmonization challenges. Sci. Total Environ. 759, 143506 https://doi.org/10.1016/j.scitotenv.2020.143506.

Huang, Y., Bird, R., Bell, M., 2009a. A comparative study of the emissions by road maintenance works and the disrupted traffic using life cycle assessment and micro-simulation. Transp. Res. Part D Transp. Environ. 14, 197–204. https://doi.org/10.1016/j.trd.2008.12.003.

Huang, Y., Bird, R., Heidrich, O., 2009b. Development of a life cycle assessment tool for construction and maintenance of asphalt pavements. J. Clean. Prod. 17, 283–296. https://doi.org/10.1016/j.jclepro.2008.06.005.

Huang, Y., Spray, A., Parry, T., 2013. Sensitivity analysis of methodological choices in road pavement LCA. Int. J. Life Cycle Assess. 18, 93–101. https://doi.org/10.1007/s11367-012-0450-7.

Huang, Y.H., 2004. Pavement Analysis and Design, second. ed. Upper Saddle River.

Huijbregts, M A J, Thissen, U., Guin, J.B., Jager, T., Kalf, D., Meent, D. Van De, Ragas, A.M.J., Sleeswijk, A.W., Reijnders, L., 2000. Priority assessment of toxic substances in life cycle assessment. Part I: calculation of toxicity potentials for 181 substances with the nested multi-media fate, exposure and effects model USES-LCA. Chemosphere 41, 541–573. https://doi.org/https://doi.org/10.1016/S0045-6535(00)00030-8.

Huijbregts, Mark A J, Thissen, U., Jager, T., van de Meent, D., Ragas, A.M.J., 2000b. Priority assessment of toxic substances in life cycle assessment. Part II: assessing parameter uncertainty and human variability in the calculation of toxicity potentials. Chemosphere 41, 575–588. https://doi.org/10.1016/S0045-6535(00)00031-X.

Inti, S., Martin, S.A., Tandon, V., 2016. Necessity of including maintenance traffic delay emissions in life cycle assessment of pavements. Procedia Eng. 145, 972–979. https://doi.org/10.1016/j.proeng.2016.04.126.

Inyim, P., Pereyra, J., Bienvenu, M., Mostafavi, A., 2016. Environmental assessment of pavement infrastructure: a systematic review. J. Environ. Manage. 176, 128–138. https://doi.org/10.1016/j.jenvman.2016.03.042.

Jelica, D., Taljegård, M., Thorson, L., Johnsson, F., 2018. Hourly electricity demand from an electric road system – A Swedish case study. Appl. Energy 228, 141–148. https://doi.org/10.1016/j.apenergy.2018.06.047.

Jiang, R., Wu, P., 2019. Estimation of environmental impacts of roads through life cycle assessment: A critical review and future directions. Transp. Res. Part D Transp. Environ. 77, 148–163. https://doi.org/10.1016/j.trd.2019.10.010.

Jones, D., 2017. Guidelines for the selection, specification, and application of chemical dust control and stabilization treatments on unpaved roads.

JPI Urban Europe Management Board, 2019. HERMES | JPI Urban Europe [WWW Document]. accessed 7.23.19. https://jpi-urbaneurope.eu/project/hermes/.

Kennedy, E., 2006. Integration of the measurement of energy usage into road design.

Kim, H.C., Wallington, T.J., Sullivan, J.L., Keoleian, G.A., 2015. Life cycle assessment of vehicle lightweighting: novel mathematical methods to estimate use-phase fuel consumption. Environ. Sci. Technol. 49, 10209–10216. https://doi.org/10.1021/acs.est.5b01655.

Komatsu, 2009. Specifications and application handbook. Tokyo.

Krantz, J., Lu, W., Johansson, T., Olofsson, T., 2017. Analysis of alternative road construction staging approaches to reduce carbon dioxide emissions. J. Clean. Prod. 143, 980–988. https://doi.org/10.1016/j.jclepro.2016.12.023.

Laurance, W.F., Clements, G.R., Sloan, S., O'Connell, C.S., Mueller, N.D., Goosem, M., Venter, O., Edwards, D.P., Phalan, B., Balmford, A., Van Der Ree, R., Arrea, I.B., 2014. A global strategy for road building. Nature 513, 229–232. https://doi.org/10.1038/nature13717.

Leontief, W., 1970. Environmental repercussions and the economic structure aninput–output approach. Rev. Econ. Stat. 52, 262–271.

Lepert, P., Brillet, F., 2009. The overall effects of road works on global warming gas emissions. Transp. Res. Part D Transp. Environ. 14, 576–584. https://doi.org/10.1016/j.trd.2009.08.002.

Li, Han, X., Jin, M., Zhang, X., Wang, S., 2019. Globally analysing spatiotemporal trends of anthropogenic PM2.5 concentration and population's PM2.5 exposure from 1998 to 2016. Environ. Int. 128, 46–62. https://doi.org/10.1016/j.envint.2019.04.026.

Liimatainen, H., van Vliet, O., Aplyn, D., 2019. The potential of electric trucks – an international commodity-level analysis. Appl. Energy 236, 804–814. https://doi.org/10.1016/j.apenergy.2018.12.017.

Liu, Q., Wu, S., Schlangen, E., 2013. Induction heating of mastic asphalt for crack control. Constr. Build. Mater. 41, 345–351. https://doi.org/10.1016/j.conbuildmat.2012.11.075.

Liu, Y., Wang, Y., Li, D., 2017. Estimation and uncertainty analysis on carbon dioxide emissions from construction phase of real highway projects in China. J. Clean. Prod. 144, 337–346. https://doi.org/10.1016/j.jclepro.2017.01.015.

Lopes, M., Serrano, L., Ribeiro, I., Cascão, P., Pires, N., Rafael, S., Tarelho, L., Monteiro, A., Nunes, T., Evtyugina, M., Nielsen, O.J., Gameiro da Silva, M., Miranda, A.I., Borrego, C., 2013. Emissions characterization from EURO 5 diesel/biodiesel passenger car operating under the new European driving cycle. Atmos. Environ. 84, 339–348. https://doi.org/10.1016/j.atmosenv.2013.11.071.

Lou, B., Barbieri, D.M., Passavanti, M., Hui, C., Gupta, A., Hoff, I., Lessa, D.A., Sikka, G., Chang, K., Fang, K., Lam, L., Maharaj, B., Ghasemi, N., Qiao, Y., Adomako, S., Foroutan Mirhosseini, A., Naik, B., Banerjee, A., Wang, F., Tucker, A., Liu, Z., Wijayaratna, K., Naseri, S., Yu, L., Chen, H., Shu, B., Goswami, S., Peprah, P., Hessami, A., Abbas, M., Agarwal, N., 2021a. Air pollution perception in ten countries during the COVID-19 pandemic. Ambio. https://doi.org/https://doi.org/10.1007/s13280-021-01574-2.

Lou, B., Sha, A., Barbieri, D.M., Liu, Z., Zhang, F., 2021b. Microwave heating properties of steel slag asphalt mixture using a coupled electromagnetic and heat transfer model. Constr. Build. Mater. 291, 123248 https://doi.org/10.1016/j.conbuildmat.2021.123248.

Lou, B., Sha, A., Barbieri, D.M., Liu, Z., Zhang, F., Jiang, W., 2021c. Improved microwave heating uniformity and self-healing properties of steel slag asphalt containing ferrite filler. Mater. Struct. 7, 1–14. https://doi.org/10.1617/s11527-020-01577-7.

Mallick, R.B., El-Korchi, T., 2013. Pavement engineering. Principles and practice, second. ed. CRC Press, Boca Raton.

Marchiori, C., Dietz, S., Tavoni, A., 2017. Domestic politics and the formation of international environmental agreements. J. Environ. Econ. Manage. 81, 115–131. https://doi.org/10.1016/j.jeem.2016.09.009.

Marion, A.M., De Lanève, M., De Grauw, A., 2005. Study of the leaching behaviour of paving concretes: Quantification of heavy metal content in leachates issued from tank test using demineralized water. Cem. Concr. Res. 35, 951–957. https://doi.org/10.1016/j.cemconres.2004.06.014.

Mijena, E.H., 2019. EPS Geofoam used in E16 Sandvika-Wøyen. In: Arellano, D., Özer, A., Bartlett, S., Vaslestad, J. (Eds.), 5th International Conference on Geofoam Blocks in Construction Applications. Springer.

Miliutenko, S., Kluts, I., Lundberg, K., Toller, S., Brattebø, H., Birgisdottir, H., Potting, J., 2014. Consideration of life cycle energy use and greenhouse gas emissions in road infrastructure planning processes: Examples of Sweden, Norway, Denmark and the Netherlands. J. Environ. Assess. Policy Manag. 16, 1450038. https://doi.org/https://doi.org/10.1142/ S1464333214500380.

Múčka, P., 2017. International roughness index specifications around the world. Road Mater. Pavement Des. 18, 929–965. https://doi.org/10.1080/14680629.2016.1197144.

Muresan, B., Capony, A., Goriaux, M., Pillot, D., Higelin, P., Proust, C., Jullien, A., 2015. Key factors controlling the real exhaust emissions from earthwork machines. Transp. Res. Part D 41, 271–287. https://doi.org/10.1016/j.trd.2015.10.002.

Myhre, G., Myhre, A., 2003. Uncertainties in radiative forcing due to surface albedo changes caused by land-use changes. J. Clim. 16, 1511–1524. https://doi.org/10.1175/1520-0442-16.10.1511.

NPRA, 2020. Trafikkdata [WWW Document]. accessed 5.31.20. https://www.vegvesen.no/fag/trafikk/trafikkdata.

NPRA, 2019. Veg- og gateutforming. Vegdirektoratet, Norway.

NPRA, 2018a. Konsekvensanalyser. Vegdirektoratet, Norway.

NPRA, 2018b. Håndbok N200 vegbygging. Vegdirektoratet, Norway.

NPRA, 2018c. Skal redusere CO2-utslippene betydelig på veganlegg [WWW Document]. accessed 5.31.20. https://www.vegvesen.no/om+statens+vegvesen/presse/nyheter/nasjonalt/skal-redusere-co2-utslippene-betydelig-pa-veganlegg.

NPRA, 2014a. Håndbok R610 Standard for drift og vedlikehold av riksveger. Vegdirektoratet, Norway.

NPRA, 2014b. Håndbok N200 vegbygging. Vegdirektoratet, Norway.

Paterson, W.D.O., 1986. International roughness index: relationship to other measures of roughness and riding quality. Transp. Res. Rec. 49–58.

Pennington, D.W., Potting, J., Finnveden, G., Lindeijer, E., Jolliet, O., Rydberg, T., Rebitzer, G., 2004. Life cycle assessment Part 2: Current impact assessment practice. Environ. Int. 30, 721–739. https://doi.org/10.1016/j.envint.2003.12.009.

Pinsonnault, A., Lesage, P., Levasseur, A., Samson, R., 2014. Temporal differentiation of background systems in LCA: relevance of adding temporal information in LCI databases. Int. J. Life Cycle Assess. 19, 1843–1853. https://doi.org/10.1007/s11367-014-0783-5.

Plati, C., 2019. Sustainability factors in pavement materials, design, and preservation strategies: a literature review. Constr. Build. Mater. 211, 539–555. https://doi.org/10.1016/j.conbuildmat.2019.03.242.

Potting, J., Birgisdottir, H., Brattebø, H., Kluts, I., Liljenström, C., Lundberg, K., Miliutenko, S., O'Born, R., Iversen, O.M., Toller, S., van Oirschot, R., 2013. LICCER final report.

Qin, Y., 2015. A review on the development of cool pavements to mitigate urban heat island effect. Renew. Sustain. Energy Rev. 52, 445–459. https://doi.org/10.1016/j.rser.2015.07.177.

Rebitzer, G., Ekvall, T., Frischknecht, R., Hunkeler, D., Norris, G., Rydberg, T., Schmidt, W.-P., Suh, S., Weidema, B.P., Pennington, D.W., 2004. Life cycle assessment Part 1: Framework, goal and scope definition, inventory analysis, and applications. Environ. Int. 30, 701–720. https://doi.org/10.1002/ad.2179.

Richard, C., Doré, G., Lemieux, C., Bilodeau, J.-P., Haure-Touzé, J., 2015. In: Albedo of pavement surfacing materials: in situ measurements. American Society of Civil Engineers, Salt Lake City, pp. 181–192.

Richardson, D.B., 2013. Electric vehicles and the electric grid: A review of modeling approaches, Impacts, and renewable energy integration. Renew. Sustain. Energy Rev. 19, 247–254. https://doi.org/10.1016/j.rser.2012.11.042.

Roshani, H., Dessouky, S., Montoya, A., Papagiannakis, A.T., 2016. Energy harvesting from asphalt pavement roadways vehicle-induced stresses: A feasibility study. Appl. Energy 182, 210–218. https://doi.org/10.1016/j.apenergy.2016.08.116.

Samferdselsdepartementet, 2018. Muligheter og barrierer for fossilfrie anleggsplasser i transportsektoren.

Santero, N.J., Harvey, J., Horvath, A., 2011a. Environmental policy for long-life pavements. Transp. Res. Part D Transp. Environ. 16, 129–136. https://doi.org/10.1016/j.trd.2010.09.005.

Santero, N.J., Horvath, A., 2009. Global warming potential of pavements. Environ. Res. Lett. 4, 7. https://doi.org/10.1088/1748-9326/4/3/034011.

Santero, N.J., Masanet, E., Horvath, A., 2011b. Life-cycle assessment of pavements. Part I: critical review. Resour. Conserv. Recycl. 55, 801–809. https://doi.org/ee.

Santero, N.J., Masanet, E., Horvath, A., 2011c. Life-cycle assessment of pavements Part II: filling the research gaps. Resour. Conserv. Recycl. 55, 810–818. https://doi.org/10.1016/j.resconrec.2011.03.009.

Sen, S., Roesler, J., 2016. Aging albedo model for asphalt pavement surfaces. J. Clean. Prod. 117, 169–175. https://doi.org/10.1016/j.jclepro.2016.01.019.

Skelton, A., 2013. EU corporate action as a driver for global emissions abatement: A structural analysis of EU international supply chain carbon dioxide emissions. Glob. Environ. Chang. 23, 1795–1806. https://doi.org/10.1016/j.gloenvcha.2013.07.024.

Šliupas, T., 2006. Annual average daily traffic forecasting using different techniques. Transport 21, 38–43. https://doi.org/10.1080/16484142.2006.9638039.

Sovacool, B.K., Noel, L., Kester, J., Zarazua de Rubens, G., 2018. Reviewing Nordic transport challenges and climate policy priorities: Expert perceptions of decarbonisation in Denmark, Finland, Iceland, Norway, Sweden. Energy 165, 532–542. https://doi.org/10.1016/j.energy.2018.09.110.

Statistics Norway, 2021. Road traffic volumes, by type of vehicle and age of vehicle 2005 - 2020 [WWW Document]. URL https://www.ssb.no/en/statbank/table/12575/tableViewLayout1/.

Stripple, H., 2001. Life cycle assessment of road - A pilot study for inventory analysis. https://doi.org/10.1177/0734242X10379146.

Suh, S., Lenzen, M., Treloar, G.J., Hondo, H., Horvath, A., Huppes, G., Jolliet, O., Klann, U., Krewitt, W., Moriguchi, Y., Munksgaard, J., Norris, G., 2004. System boundary selection in life-cycle inventories using hybrid approaches. Environ. Sci. Technol. 38, 657–664. https://doi.org/10.1021/es0263745.

Taljegård, M., Thorson, L., Odenberger, M., Johnsson, F., 2019. Large-scale implementation of electric road systems: associated costs and the impact on CO2 emissions. Int. J. Sustain. Transp. 1–14 https://doi.org/10.1080/15568318.2019.1595227.

Tarefder, R.A., Bateman, D., 2010. Design of optimal perpetual pavement structure. J. Transp. Eng. 138, 157–175. https://doi.org/10.1061/(asce)te.1943-5436.0000259.

Tatari, O., Nazzal, M., Kucukvar, M., 2012. Comparative sustainability assessment of warm-mix asphalts: a thermodynamic based hybrid life cycle analysis. Resour. Conserv. Recycl. 58, 18–24. https://doi.org/10.1016/j.resconrec.2011.07.005.

Teknologirådet, 2012. Teknologirådet | Norge 2030 arkiver [WWW Document]. URL https://teknologiradet.no/category/norge-2030/ (accessed 9.6.20).

Thives, L.P., Ghisi, E., 2017. Asphalt mixtures emission and energy consumption: A review. Renew. Sustain. Energy Rev. 72, 473–484. https://doi.org/10.1016/j.rser.2017.01.087.

Thom, N., 2014. Principles of Pavement Engineering, second. ed. ICE, London.

Toller, S., 2018. Klimatkalkyl - Calculating greenhouse gas emissions and energy use of transport infrastructure from a life cycle perspective, version 5.0 and 6.0. Borlänge.

Trani, M.L., Bossi, B., Gangolells, M., Casals, M., 2016. Predicting fuel energy consumption during earthworks. J. Clean. Prod. 112, 3798–3809. https://doi.org/10.1016/j.jclepro.2015.08.027.

Trupia, L., Parry, T., Neves, L.C., Lo Presti, D., 2017. Rolling resistance contribution to a road pavement life cycle carbon footprint analysis. Int. J. Life Cycle Assess. 22, 972–985. https://doi.org/10.1007/s11367-016-1203-9.

Wang, C., 2013. Differential output growth across regions and carbon dioxide emissions: Evidence from U.S. and China. Energy 53, 230–236. https://doi.org/10.1016/j.energy.2013.02.044.

Wang, F., Xie, J., Wu, S., Li, J., Barbieri, D.M., Zhang, L., 2021. Life cycle energy consumption by roads and associated interpretative analysis of sustainable policies. Renew. Sustain. Energy Rev. 141, 110823 https://doi.org/10.1016/j.rser.2021.110823.

Wang, H., Al-Saadi, I., Lu, P., Jasim, A., 2020. Quantifying greenhouse gas emission of asphalt pavement preservation at construction and use stages using life-cycle assessment. Int. J. Sustain. Transp. 14, 25–34. https://doi.org/10.1080/15568318.2018.1519086.

Wang, T., Lee, I.S., Kendall, A., Harvey, J., Lee, E.B., Kim, C., 2012. Life cycle energy consumption and GHG emission from pavement rehabilitation with different rolling resistance. J. Clean. Prod. 33, 86–96. https://doi.org/10.1016/j.jclepro.2012.05.001.

Xu, X., Akbarian, M., Gregory, J., Kirchain, R., 2019. Role of the use phase and pavement-vehicle interaction in comparative pavement life cycle assessment as a function of context. J. Clean. Prod. 230, 1156–1164. https://doi.org/10.1016/j.jclepro.2019.05.009.

Yu, B., Lu, Q., 2014. Estimation of albedo effect in pavement life cycle assessment. J. Clean. Prod. 64, 306–309. https://doi.org/10.1016/j.jclepro.2013.07.034.

Yu, B., Lu, Q., 2012. Life cycle assessment of pavement: methodology and case study. Transp. Res. Part D Transp. Environ. 17, 380–388. https://doi.org/10.1016/j.trd.2012.03.004.

Yu, B., Wang, S., Gu, X., 2018. Estimation and uncertainty analysis of energy consumption and CO2 emission of asphalt pavement maintenance. J. Clean. Prod. 189, 326–333. https://doi.org/10.1016/j.jclepro.2018.04.068.

Yuan, C., Wang, E., Zhai, Q., Yang, F., 2015. Temporal discounting in life cycle assessment: a critical review and theoretical framework. Environ. Impact Assess. Rev. 51, 23–31. https://doi.org/10.1016/j.eiar.2015.01.001.

Zhang, H., Lepech, M.D., Keoleian, G.A., Qian, S., Li, V.C., 2010. Dynamic life-cycle modeling of pavement overlay systems: capturing the impacts of users, construction, and roadway deterioration. J. Infrastruct. Syst. 16, 299–309. https://doi.org/10.1061/(ASCE)IS.1943-555X.0000017.