Available online at www.CivileJournal.org

Civil Engineering Journal

(E-ISSN: 2476-3055; ISSN: 2676-6957)

Vol. 8, No. 06, June, 2022

Review Article

Life Cycle Assessment in Road Pavement Infrastructures: A Review

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Received 01 April 2022; Revised 26 May 2022; Accepted 29 May 2022; Published 01 June 2022

Abstract

The need to meet society's demands for road infrastructure while minimizing the resulting environmental impacts is a source of great complications. In this context, Life Cycle Assessment (LCA) can be useful by applying a set of rules and processes for the environmental assessment of projects. The objectives of this study were to present the main environmental impact categories associated with emissions from the life cycle phases of a road pavement and how to estimate them. In addition, this paper provides examples of LCA applications on these infrastructures. In view of the evolution of research on LCA, a compilation was made on: the main categories of environmental impact associated with emissions; phases of life cycle impact assessment; and procedures and methods of impact estimation. The impact categories presented are associated with climate change, acidification, ozone depletion, tropospheric ozone formation, eutrophication, and Particulate Matter Formation. Not all methods are able to generate indicators for all types of impact and, depending on the type of materials and services that make up the inventory of the alternatives analyzed, one specific method may be more appropriate to use. The conclusions are that for each environmental impact, the results depend on the input parameters, such as energy flows and materials, along with their processing by methods of life cycle impact assessment. Besides this, despite the great diversity of the databases for the steps of life cycle assessment of roadway pavement, there is a general consensus about the nature of these steps.

Keywords: Life Cycle; Infrastructure; Environmental Impact; Transport.

1. Introduction

Because there is a limit on the ability of the biosphere to absorb the effects of human activities, and because these actions are mutable and subordinated to the degree of technological development and social, economic, and cultural organization, the concept of sustainable development has emerged. It consists of the idea that it is possible, through the combination of supply and demand management of productive resources and incentives for technological improvements, to generate economic growth for the current generation without compromising the ability of future generations to meet their needs [1].

Life cycle assessment (LCA) is inserted in this context. The processes and rules for conducting LCA were originally defined by the International Organization for Standardization (ISO) in its family of standardization [2]. The criteria for carrying out LCA are general since the objective is to guide analysis of any type of undertaking. Therefore, its application in pavement projects requires very precise specifications. The orientation is generally developed by the relevant industries and other stakeholders, such as researchers and public agencies [3].

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http://dx.doi.org/10.28991/CEJ-2022-08-06-015

Interest has been growing among transportation planners to determine the environmental impacts generated by all the steps of the life cycle of transportation infrastructure, from extraction until final disposal or recycling of materials. In this respect, although the environmental impact of products or services could be determined by other methods, LCA has gained space as the most appropriate tool to accomplish this type of task since it is able to qualify, quantify, and compare the repercussions of the structures studied. Finally, this type of capacity allows determining how a project can be implemented while minimizing the negative impacts on the environment [4, 5]. According to Alshehry & Belloumi, 2017 [6], 20% of global energy resource consumption and 25% of global GHG emissions are associated with transportation systems. However, 75% of those emissions come from road systems. In addition, pavement construction is recognized as one of the three most relevant activities in terms of natural resource consumption and, specifically within the road pavement life cycle, pavement construction can emit up to twice as many pollutants as motor vehicle operation [7, 8].

A road pavement is a layered structure that is generally sub-base, sub-base, base and surface course. As the layers underlying the surface course generally do not exert much influence on design processes, one of the main ways of classifying pavement is associated with the material that makes up this layer, which can be asphalt concrete and conventional concrete mixes [9, 10]. In Brazil, 65% of freight transport and 95% of passenger transport is carried out by road mode. Brazilian's road density if about 25,1 km/1000 km², with 99% asphalt-paved. In comparison, to other countries like China, USA, Russia, Argentina and Canada they have, respectively, 452,1 km/1000 km², 437,8 km/1000 km², 54,3 km/1000 km², 42,3 km/1000 km² and 41,6 km/1000 km² with some type of surface course, Brazil have much to expand [11].

Since asphalt-paved roads are more common, this study may focus on this type of pavement. Therefore, it is necessary to point out that asphalt mixtures are usually composed of aggregates, fillers, binders, and sometimes additives. Approximately 85% to 95% of the mix is composed of aggregate and fillers, the rest is filled by asphalt [9, 10, 12].

Chen et al. 2021 [13] analyzed the effect of global warming on asphalt-paved roadway deterioration. In this regard, they used a mechanistic-empirical pavement design method to simulate the effect of temperature. They concluded that an increase in global temperature would accelerate the deterioration of asphalt pavement leading to an escalation in maintenance demand, which would consequently require more raw material, plant production, transportation, and field construction. This growth in the amount of services generates an increase in the amount of CO_2 emitted over the life cycle of the pavement, which, although it performs better in the use phase, does not pay off. It is evident then, that the life cycle of road pavement influence and are affected by climate change. In addition to these impacts such as acidification and particulate matter emissions are widely analyzed [14].

As a contribution to less environmentally offensive roadway, this article presents a short review of concepts and paradigms for conducting life cycle assessment, focused on roadway infrastructure. The objectives were to present the main midpoint environmental impact category associated to emissions, the main methods used to translate the effects of human activities into the units generally used for each environmental impact and the life cycle stages usually adopted in life cycle assessment of a roadway pavement. In addition, this paper brings some examples of LCA searches with their combinations of sources inventories bases, stapes of life cycle considered, methods to estimate impacts. The article is organized into five sections including this introduction. Section 2 defines the general concepts for conducting life cycle assessment for any type of product or service; section 3 identifies some specifications necessary to apply LCA to roadway pavement products; section 4 summarizes some examples of studies that have applied LCA for this purpose; and section 5 contains our conclusions and some proposals for future works.

2. Life Cycle Assessment

Life cycle assessment can be subdivided into four steps: objectives and scope; life cycle inventory; environmental impact assessment; and interpretation. Figure 1 depicts a graphic representation of the LCA steps and their interdependence. The step of defining the objectives and scope consists of determining parameters, such as: (1) functional units, which are connected to a specific input or output, to enable comparison between different projects, such as kilometers of road constructed per CO_2 equivalent emitted; (2) frontiers of the system, among them the life cycle phases of the product or service and the types of impacts considered; (3) period of evaluation of the product, which in the case of pavement can extend beyond the service life; and (4) general specifications, such as a complete description of the data sources, methods and tools used to guarantee the reproducibility, replicability and auditing of the studies and evaluations [15, 16].

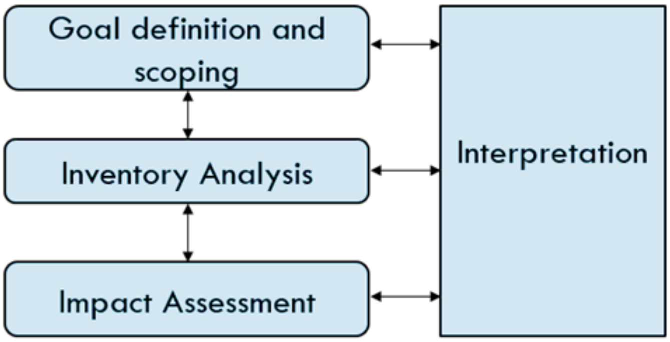

Figure 1. Structure of a Life Cycle Analysis- Source (adopted from [17, 18])

A life cycle inventory (LCI) is basically a list of inputs and outputs associated with all the steps of the LCA of a determined product [19]. There are three approaches most often applied for LCI. The first is known as process analysis or the bottom-up approach, in which the life cycle of the product is segmented into various production subsystems. The second is the top-down approach, which is based on macroeconomic diagnoses through input-output analysis. The third method incorporates characteristics of the first two procedures [20, 16].

Different substances may have the ability to generate the same environmental effects, but with different potentials. In view of this, standardization is necessary. In most cases, the intensity of the effects that a given quantity of a given substance causes on an environmental quality parameter is taken as the basis. Each effect then has its own basic substance of comparison. In addition, the same substance can contribute to several negative impacts. For a deeper understanding of the theory adopted by the life cycle assessment it is important to note that each environmental impact will have consequences on areas of protection. Usually, but not exclusively, these areas are: usually human health; ecosystem quality or natural environment; natural resources and ecosystem services. It is evident that each intermediate impact can affect more than one area of protection [19]. In this respect, Table 1 reports some of the main midpoint environmental impact category associated to emissions and Ecosystem quality or natural environment.

Table 1. Main midpoint environmental impact category associated to emissions *

Midpoint Environmental Impact	Characterization Factor	Unit	Area of Protection	References
Climate Change	Global Warming Potential (GWP)	kg CO_2-eq	Ecosystem quality or natural environment	IPCC, 2014 [21]
Stratospheric Ozone Depletion	Ozone Degradation Potential (ODP)	kg CFC-11-eq		Hauschild et al. 2018 [19]
Photochemical Ozone Formation	Photochemical Formation Potential (POPC)	kg NO_x-eq		Van Zelm et al. 2016 [22]
Acidification	Acidification Potential (TAP)	kg SO_2-eq		Roy et al. 2014 [23]
Eutrophication	Freshwater Eutrophication Potential (FEP)	kg PO_4-eq		Helmes et al. 2012 [24]
Particulate Matter Formation	Particulate Matter Formation Potential (PMFP)	kg $PM_{2,5}$-eq		Van Zelm et al. 2016 [22]

* Source: Adapted from [25-28].

Life cycle impact assessment phase apply procedures that transform different emissions in a cause-effect chain into different estimates of environmental impacts of interest susceptible to assessment. An example is the conversion of direct emissions of one ton of any gas into a carbon dioxide equivalent (CO_2eq) to determine the potential contribution to the greenhouse effect, such as methane gas (CH_4). This conversion enables comparing different substances from the standpoint of global warming potential. This step tends to be highly automated, having a great amount of different computer programs available, depending on the product analyzed and the impacts targeted for estimation [19]. Table 2 exhibits the methods developed to translate the effects of human activities into the units generally used for each environmental impact. It is pertinent to point out that for each midpoint environmental impact there is a diversity of models and considerations. For this reason, but not only, comparisons between different studies should be made with caution, as each method may use different procedure to estimate each midpoint environmental impact. In addition, it is important to note that not all methods are able to generate indicators for all types of impact. Another important issue is that, depending on the type of materials and services that make up the inventory of the alternatives analyzed, one specific method may be more appropriate to use [15, 19].

Table 2. Methods developed to translate the effects of human activities into the units generally used for each environmental impact*

Method	Name	Description	Developer	Year	Source
TRACI	Tool for Reduction and Assessment of Chemical and other environmental Impacts	An LCA program based on SimaPro specifically for use in the USA.	U.S. Environmental Protection Agency (EPA)	1995	Bare, 2002 [29]
Eco-indicator 99	———	The methodological procedure adopts a combination implementation of the end environmental impact-oriented approach.	Pré Consultants (product ecology consultants)	1997	Goedkoop et al. 1998 [30]; Goedkoop & Spriensma 2001 [31]
ERM	Elementary Road Modulus	A parametric environmental assessment tool developed by replicating LCA and adapted specifically for road structures.	Laboratoire Central des Ponts et Chaussées (LCPC)	1998	Hoang et al. 2005 [32]
CML	Centrum Milieukunde Leiden	Developed determination of intermediate environmental impacts.	Institute of Environmental Sciences at the University of Leiden	2001	Guinée et al. 2002 [33]; VAN Caneghem et al. 2010 [34]
Athena	Athena Impact Estimator	A free LCA software application aimed specifically at the construction and maintenance stages of highways in Canada and the USA.	Athena Sustainable Materials Institute	2002	Stek et al. 2011 [35]
PaLATE	Pavement Lifecycle Assessment Tool for Environmental and economic effects	An Excel®-based LCA tool focusing on economic and environmental effects.	University of California, Berkeley	2003	Horvath, 2004 [36]; Muench, 2010 [37]
ROAD-RES	Road construction and disposal of residues	An LCA tool focused on comparing the utilization of waste from incineration processes and virgin materials.	Technical University of Denmark	2005	Birgisdottir, 2005 [38]; Birgisdottir et al. 2007 [39]; Muench, 2010 [37]
ReCiPe	———	The ReCiPe LCA method was developed to provide factors to characterize intermediate and final environmental impacts.	RIVM, Radboud University Nijmegen, Leiden University and Pré Consultants.	2008; updated 2016	Goedkoop et al. 2009 [40]; Goedkoop et al. 2013 [41]; Huijbregts et al. 2016 [42]
ECORCE	ECO-comparator applied to Road Construction and Maintenance	A JAVA®-based LCA tool dedicated to road pavement for the construction and maintenance phases with a focus on material, water and energy reduction.	French Institute of Science and Technology in Transportation, Planning and Networks	1.0 (2008); 2.0 (2013); M (2014)	Jullien et al. 2015 [43]
CHANGER	Calculator for Harmonised Assessment and Normalisation of Greenhouse-gas Emissions for Roads	A calculation tool for monitoring, estimations, evaluation and normalization of GHG emissions from road construction.	International Road Federation (IRF)	2009	Huang et al. 2013 [44]
Roadprint	———	A free LCA software for evaluating new and rehabilitated road pavement, which can be considered as an evolution of PaLATE.	University of Washington	2012	Muench et al. 2014 [45]
AsPECT	Asphalt Pavement Embodied Carbon Tool	An LCA tool for calculating carbon dioxide equivalent emissions from asphalt mixtures.	Transport Research Laboratory	2009	Nicuţă, 2011 [46]
PE-2	Project Emission Estimator	Pavement GHG emissions monitoring program.	Michigan Technological University	2012	Mukherjee & Cass, 2012 [47]; Mukherjee et al. 2013 [48]
EcoConcrete	Eco-friendly Concrete	Interactive Excel®-based tool specially designed for quantifying the life cycle environmental impacts of concrete products.	Joint Project Group (JPG)	——	Evangelista & De Brito, 2007 [49]
IMPACT 2002+	———	The methodological procedure adopts an implementation through a combination of the approach to intermediate and final environmental impacts.	Swiss Federal Institute of Technology Lausanne (EPFL), currently maintained and improved by IMPACT Modeling Team.	——	Jolliet et al. 2003 [50]; Humbert et al. 2012 [51]

* Source: Adapted from [15, 25, 28, 52, 53].

Hoxha et al. 2021 [54] reviewed Life cycle assessment of roads exploring research trends and harmonization challenges. They concluded that, although theoretically unexpected, the software used for analysis affects the results and possible comparisons between studies, even if they contain the same databases and methods. In addition, they noted that most studies estimated impacts on climate change, leaving other impacts relegated to the background. Furthermore, they pointed out that publicizing the impacts that road infrastructure can generate for climate change is important as it can raise awareness.

Finally, the objective of the interpretation step is to summarize, identify and evaluate the results of the LCI and LCIA, and to draw some conclusions regarding the project of interest. This step generally consists of three elements: identification of relevant questions based on the results of the LCI and LCIA; evaluation of the sensitivity of the problems identified and verification of the consistency and completeness of the results; conclusions, limitations of the study and recommendations for future research [15].

3. Life Cycle Assessment on Pavement

LCA is a structured method to determine the types and quantities of impacts generated during the life cycle of a supply chain, by examining the inputs and outputs of a product or system. In the case of roadway pavement, the life cycle can cover the following phases: (1) extraction of raw materials (virgin inputs); (2) transport of inputs; (3) milling or other processing of the input materials; (4) transport of the processed paving materials; (5) construction of the pavement; (6) maintenance and recuperation; (7) operation; (8) recycling; (9) demolition; and (10) reconstruction [3, 16, 55].

Figure 2 (adapted from [15, 18, 55]) contains a representation of a roadway pavement life cycle phases connection and the processes customarily allocated to them. It is possible to note the phases chronological order of linkage and the contribution of a single phase to multiple other phases (e.g., the production of materials feeds the construction and maintenance phases). Another observation is the participation of transport in all the phases, although with different relevance levels. Finally, the phases of use/operation and maintenance/recuperation, although occurring in the same period (during the life cycle of the pavement), are considered separately, in attempt to rationalize organization, since the desire is to verify the effects of different processes that in final analysis are associated with the users or managers of the road. The reason is that the flows of materials and energy that feed each phase have different levels, and hence different environmental impacts.

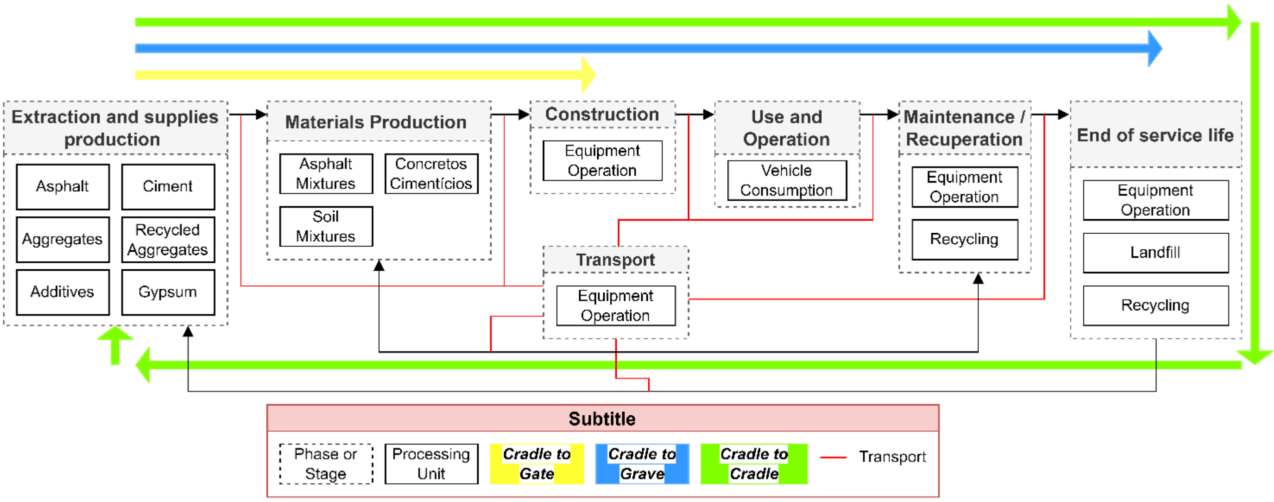

Figure 2. Life cycle stages Illustration of a highway pavement

According to Xiao et al. 2019 [15], a LCA of a pavement have different designations depending on the steps life of cycle included into the analysis, namely: (i) from cradle to gate, when the phases of extraction, processing of inputs and construction are considered; (ii) from cradle to grave, when the phases of use/operation, maintenance/recuperation and end of life are added to those mentioned in (i), without considering total recycling of the elements composing the pavement; and (iii) from cradle to cradle, when the study covers all the phases plus the recycling of the elements that compose the pavement, to start the chain again.

There are at each stage of the pavement life cycle a number of processes. Figure 3 attempts to illustrate the fact that each process requires different types and amounts of materials and energy to complete them. For example, to prepare the asphalt mixture it is necessary to have asphalt, aggregates and additives, which need to be heated and mixed together. The result is not only the desired product, but also substances that can affect the soil, land and air [19, 56].

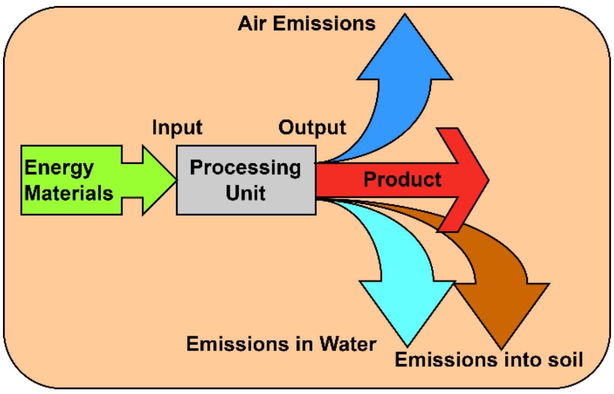

Figure 3. Generic procedural unit illustration regarding its inputs and outputs from an environmental point of view

The stage of extraction and supplies production includes the processes of extraction and beneficiation of raw materials to produce the materials that will be used in the phases of construction, maintenance and recuperation of the pavement. These mainly consist of mixtures of aggregates with a wide granulometric range and asphaltic binders [3, 57].

The phase of materials production has the objective of gathering the different inputs from the extraction phase and processing. With regard to asphaltic mixtures, the typical steps are: (1) drying and heating of the aggregates; (2) heating of the binder; and (3) mixture of the aggregates with binder. With regard to the materials composing the other pavements layers namely, base, sub-base and subgrade, the following steps occur: (4) granulometric stabilization; and (5) chemical stabilization [18]. The transport of materials is involved in all the other steps of the life cycle of a roadway pavement. For example, in the case of the construction of a new pavement or maintenance/recuperation of an old one, it will be necessary to transport the binder and different aggregates to the worksite. In the case of maintenance/recuperation, it will also be necessary to transport old material for recycling or final disposal. The environmental impacts of this transport will be mainly influenced by: engine technology of the transport vehicle; load capacity of the vehicle; shifting distances; transportation speed and weight of the materials to be carried [57].

The environmental impacts usually considered in construction phase and maintenance/recuperation phase depends on equipment combustion: (1) of the fuel used by the construction equipment at the site and vehicles that carry the materials; and (2) the extra fuel consumed by vehicles that must wait idling, travel at reduced speed and/or take detours around the construction site [3, 57]. Some of the main aspects that directly interfere in the intensities of environmental impacts in practically all stages are: service life, with several methods for estimation; frequency and type of maintenance, which also has a great diversity of possibilities and effects [58]. During pavement use stage, impacts are normally associated to vehicles consumption affected by vehicles-pavement interactions. Fuel consumption can vary due to: conditions and characteristics of vehicles (shock absorbers, brakes, tire tread, engine); preservation or deterioration of the surface of pavement, that increases or decreases rolling resistance (roughness, macrotexture); geometric characteristics of the road, such as curves and ascending and descending ramps; pavement such as albedo or reflectance, heating capacity and thermal conductivity [3, 57].

Table 3 presents some pavement life cycle assessment studies. Consensus can be observed on phases definitions, but there is no agreement on which steps to be taken account. This seems to corroborates that, these aspects must be determined by the team of researchers according to the objectives and scope of the study. Other aspect to note is that the majority decided to estimate climate change, acidification contributions and energy consumption. Those aspects are in line with Meijer et al. (2018) [14].

Table 3. Papers Collection that applied LCA in highway pavement studies, showing the steps considered and the environmental impact indicators used*

Studies	Life cycle steps						Environmental Impact Indicators									
	Extraction / Production	Transport of materials	Construction	Use	Maintenance	Recycling	Greenhouse Gases (CO_2 eq)	Energy Consumption (MJ)	Carbon Dioxide (CO_2)	Carbon Monoxide (CO)	Methane (CH_4)	Sulfur Oxides (SOx)	Nitrogen Oxides (NOx)	Particulate Matter (PM10)	Nitrous Oxide (N_2O)	Volatile Organic Compounds (VOC)
Huang et al. (2009) [59]	x	x	x					x	x			x	x			
Yu et al. (2012) [60]	x	x	x	x	x	x			x	x	x	x	x	x	x	
Yu et al. (2013) [61]		x	x	x	x	x	x	x	x	x	x	x	x			
Chou et al. (2013) [62]	x				x				x	x			x	x		
Yu et al. (2014) [63]		x	x	x		x			x							
Araújo et al. (2014) [64]	x	x	x	x	x	x		x								
Santos et al. (2015a) [57]	x	x	x	x	x	x	x	x	x	x	x	x	x		x	
Santos et al. (2015b) [65]	x	x	x	x	x	x	x	x	x	x	x	x	x			
Liu et al. (2015) [66]	x	x	x	x	x	x	x									
Mauro et al. (2016) [67]	x	x	x	x	x	x		x	x	x		x	x	x		
Chen et al. (2016) [68]	x		x	x		x			x	x	x	x	x	x		
Chong & Wang (2017) [52]	x	x	x	x	x	x	x	x								
Santos et al. (2017b) [69]	x	x	x	x	x	x	x									
Moretti et al. (2017) [70]	x	x					x	x				x				
Liu et al. (2018) [71]	x		x				x									
Hong et al. (2018) [72]	x	x	x	x	x	x		x								
Gulotta et al. (2019) [73]	x	x	x		x	x		x								

Wang et al. (2019) [74]	x	x	x	x	x			x	x		x					
Cong et al. (2020) [56]	x	x	x		x	x		x	x	x	x	x	x		x	
Huang et al. (2021) [75]	x	x	x	x	x		x	x		x	x	x	x	x	x	x
Total	**18**	**17**	**18**	**14**	**15**	**14**	**8**	**13**	**11**	**9**	**8**	**10**	**10**	**5**	**4**	**1**

*Source: Adapted from [76].

4. Life Cycle Assessment on Pavement Applications

Table 4 presents a compilation of pavements life cycle assessments studies exposing: objectives and scopes; sources of data used; LCIA method adopted. Objectives includes comparison of asphalt mills versus asphalt plants and virgin aggregates versus recycled aggregates. The majority of works estimated contributions made on climate change, acidification, degradation of the ozone layer, formation of tropospheric ozone and eutrophication. Regarding to data inventories, there was no consensus on national and international databases use. About LCIA method, no particular preference was observed.

Table 4. Databases, LCA methods, software and estimated impacts when performing road pavements LCA*

Objectives	Life cycle Steps	Database Source	LCIA Methods	Software	Environmental Impact Indicators	References
Comparison of the environmental impacts associated with the production of HMA with virgin and recycled aggregates.	Cradle-to-site: Transportation; extraction & machining; construction	Regional data; Ecoinvent v.3 e USLCI (United States life cycle inventory)	TRACI	SimaPro	ODP, GWP, POPC, TAP, FEP, Ecotoxicity, Fossil Fuel Depletion, Human Health Damage	Vega et al. 2020 [28]
Comparison of the economic and environmental impacts of using different materials for pavement layers.	Cradle-to-site: Transportation; extraction & machining; construction	Regional data, Ecoinvent v.3, literature review	CML Baseline	SimaPro	GWP, Fossil Fuel Depletion	Nascimento et al. 2020 [76]
Comparison of the environmental impacts associated with the production of HMA with virgin and recycled aggregates.	Cradle-to-gate: Extraction; crushing (RCA); transport to storage	Regional data e Ecoinvent v.3	IMPACT 2002+	SimaPro	GWP, TAP, ODP, FEP, Human Health Damage, Ecotoxicity, Fossil Fuel Depletion	Martinez-Arguelles et al. 2019 [27]
Comparison of the economic, social, and environmental impacts associated with the use of RCA on the base paving (PCC) with conventional ones.	Cradle-to-grave: Machining; construction; use; maintenance; end-of-life	Regional data; Oklahoma DOT AADT Traffic Counts	TRACI	EIO-LCA model developed by CMU	GWP, TAP, ODP, POPC, FEP, Danos a saúde humana, Ecotoxicity	Shi et al. 2019 [77]
Comparison of the environmental impacts associated with the production of HMA with virgin and recycled aggregates.	Cradle-to-site: Demolition site transportation (RCA); extraction and machining; disposal (RCA); concrete plant transportation; transportation	Regional data; Ecoinvent v.3 e USLCI (United States life cycle inventory)	IMPACT 2002+	SimaPro	GWP, Human Health Damage, Ecotoxicity, Fossil Fuel Depletion	Rosado et al. 2017 [78]
Comparison of the environmental impacts associated with the production of HMA with virgin and recycled aggregates.	Cradle-to-gate: Extraction and machining; transportation to the mill; production at the mill.	literature review, Ecoinvent v.3 e ELCD (European life cycle database)	CML baseline method and Cumulative Energy Demand	SimaPro	ADP, GWP, ODP, POPC, TAP, FEP	Braga et al. 2017 [79]
Compare the differences between the environmental impacts generated by recycled and virgin aggregates.	Cradle-to-site: Extraction of materials; crushing; transportation through all stages until construction.	CLP (Chinese Light and Power), CLCD (Chinese life cycle database) e ELCD (European life cycle database)	IMPACT 2002+	SimaPro	GWP, TAP, ODP, POPC, FEP, Ecotoxicity, Fossil Fuel Depletion Human Health Damage	Hossain et al. 2016 [80]
Compare the environmental impacts associated aggregates for asphalt mixtures: (i) virgin; (ii) recycled in a mill plant; (iii) recycled in a mobile plant.	Cradle-to-site: Transport from demolition site (RCA); quarrying and machining; cradle-to-grave (RCA); transport from concrete plant; transport to construction site.	Regional data	Eco-indicator 99, CML Baseline and Cumulative Energy Demand	SimaPro	GWP, TAP, ODP, FEP, Human Health Damage, Ecotoxicity, Fossil Fuel Depletion.	Estanqueiro et al. 2016 [81]

*Source: Adapted from [28].

5. Conclusion

Transport infrastructure affects the environment in several ways. Directly, by demanding natural resources that will form the materials used in the construction and conservation of pavements. Indirectly, by demanding fuel to operate vehicles and construction equipment. To decrease the negative environmental effects of infrastructure, it is necessary to compare which alternative designs cause the lowest environmental impacts. That is the context of the application of life cycle assessment. This article presented a short review of concepts and paradigms for conducting life cycle assessments, focusing on highway infrastructure.

A compilation of the main midpoint environmental impact category associated with emissions was shown. As discussed, different substances may have the ability to generate the same environmental effects but with different potentials. Each effect then has its own basic substance of comparison. The impact categories presented are associated with climate change, acidification, ozone depletion, tropospheric ozone formation, eutrophication, and Particulate Matter Formation.

The life cycle impact assessment phase applies procedures that transform different emissions in a cause-effect chain into different estimates of environmental impacts of interest susceptible to assessment. This step tends to be highly automated, with a greater number of different computer programs available depending on the product analyzed and the impacts targeted for estimation. Not all methods are able to generate indicators for all types of impact and, depending on the type of materials and services that make up the inventory of the alternatives analyzed, one specific method may be more appropriate to use. Comparisons between different studies should be made with caution, as each method may use a different procedure to estimate each midpoint environmental impact. In addition, the methods used to determine these indicators vary widely in the sample analyzed, indicating lack of consensus about it and constant technology update.

There is no way to indicate the best database to use is to recommend the adoption of a database that best represents the alternatives, since the precision of the results of LCA depends on the reliability of the data employed for characterization of the inputs. The diversity of selections that have to be made by researchers to apply the LCA methodology and the inherent diversity of the infrastructure project alternatives being compared makes quantitative comparisons difficult, because the final analysis will correspond to the characteristics of the chosen parameters for the inventory. In order to use LCA as a reliable and replicable tool to evaluate the environmental impacts that highways can generate, all the parameters and considerations adopted to perform the analysis must be established and made evident. Finally, a proposal for future studies would be to evaluate the effects on the LCA of a pavement that would suffer under the variation of construction materials, construction techniques, and pavement management strategies.

6. Declarations

6.1. Author Contributions

Conceptualization, B.G.G., and M.D.; methodology, B.G.G., and M.D.; software, B.G.G., and M.D.; validation, B.G.G., and M.D.; formal analysis, B.G.G., and M.D.; investigation, B.G.G., M.D., and M.A.V.S.; resources, B.G.G., M.D., and M.A.V.S.; data curation, B.G.G., M.D., and M.A.V.S.; writing—original draft preparation, B.G.G., M.D., and M.A.V.S.; writing—review and editing, B.G.G., M.D., and M.A.V.S.; visualization, M.A.V.S.; supervision, M.A.V.S. All authors have read and agreed to the published version of the manuscript.

6.2. Data Availability Statement

The data presented in this study are available on request from the corresponding author.

6.3. Funding

This study was financed in part by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior – Brasil (CAPES) – Finance Code 001 and Conselho Nacional de Desenvolvimento Científico e Tecnológico – Brasil (CNPq).

6.4. Conflicts of Interest

The authors declare no conflict of interest.

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