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Abstract

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Keywords	Life cycle assessment (LCA); roads; sustainable development; green infrastructure.
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Estimation of environmental impacts of roads through life cycle assessment: a critical review and future directions

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Abstract: Motivated by the lack of a systematic analysis of the use of life cycle assessment (LCA) to estimate the environmental impacts of roads, this study conducts a critical review to examine the methods, common practices, limitations, and underlying reasons, so that future directions can be recommended. In this work, 94 papers that adopt LCA methods to assess the environmental impacts over the whole life cycle of roads were analyzed. The results demonstrate that the process-based LCA remains the most commonly adopted LCA method; however, the hybrid LCA has been gradually recognized. After examining the goal and scope definition, life cycle inventory, life cycle impact assessment, and life cycle interpretation of these studies, it was found that the current LCA applications in roads face limitations owing to the inconsistent and inappropriate selection of the functional unit, limited consideration of the maintenance and repair, use, and end-of-life phases, limited reporting of data sources, lack of standardized impact assessment procedures, and lack of sensitivity and uncertainty analyses. These limitations can be attributed to the lack of a standardized LCA procedure for roads. There is also a lack of LCA studies focusing on network-level analysis, which may restrict the use of LCA to assist policy making in road planning and management. In addition, the time effect is rarely considered to reflect the dynamic changes of environmental impacts over the project life cycle. Therefore, future directions are recommended accordingly. Improvements in these areas are expected to generate more reliable LCA results for informed decision making.

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1 Introduction

Roads play a significant role in the transport network as people increasingly rely on vehicles for daily travel. A large network of roads causes adverse environmental impacts, such as global warming, energy consumption, landscape transformation, and soil acidification (Findlay and Bourdages, 2000; Santos et al., 2015). Construction works and regular maintenance of roads require materials that are produced through highly carbon-intensive and energy-demanding processes (Santos et al., 2015). In addition, road networks worldwide are also a major cause of significant biodiversity loss due to movement of species, habitat fragmentation, and increase of human access to existing natural habitats (Alkemade et al., 2009; Findlay and Bourdages, 2000). Green designs and practices in the road sector are highly encouraged by transportation authorities to mitigate the adverse environmental impacts (Wu et al., 2017).

The life cycle assessment (LCA) approach examines the environmental impacts of products/processes (Santero et al., 2011b). Unlike other sectors, the use of LCA in road assessment is still in its early stage. The first LCA study on roads was conducted in the 1990s (Inyim et al., 2016). Over the last two decades, LCA has attracted increasing interest as a method to evaluate the sustainability of roads. The current application of LCA in road evaluation often follows the ISO 14044 (2006) standard. However, this standard is primarily designed for the environmental assessment of manufactured products rather than infrastructure projects such as roads. As roads have their own unique characteristics, existing LCA practices may not be suitable in this area (Batouli and Mostafavi, 2017).

For example, when defining the goal and scope of an LCA analysis, it is a common practice to set a pre-defined analysis period and functional unit (FU) for a given product/process (ISO 14044, 2006). However, for road projects, to ensure the continued functioning of a road, maintenance and rehabilitation are needed at regular intervals and road decommissioning is relatively rare. It is therefore difficult to pre-define a strict system boundary for a road (Batouli and Mostafavi, 2017). Furthermore, the performance of a road changes as the road condition deteriorates. The widely used FUs, including length (e.g., lane-kilometer, lane-mile) and area (e.g., square-meter), are unable to capture such dynamic changes (Batouli and Mostafavi, 2017). More importantly, owing to the changing road performance, the maintenance strategies and their frequency and impact on the sustainability of roads are difficult to be accurately predicted and modeled. However, these problems, along with their root causes, have not been widely recognized in current studies. Recently, researchers began to realize these limitations, such as the inconsistent selection of FUs and system boundaries (Inyim et al., 2016). Therefore, a systematic review of the current development and implementation of LCAs in road projects is needed to comprehensively explore their limitations so that future studies can better address them.

For now, there are already a few isolated publications that have reviewed the existing LCA research on roads or road pavements. For example, Anthonissen et al. (2016), Balaguera et al. (2018), and Jamshidi et al. (2017) conducted reviews on environmental impacts of sustainable alternative construction methods or construction materials for roads. Santero et al. (2011a, 2011b) reviewed 15 pavement LCA related works, pointing out several limitations of the reviewed studies and environmental impact contributors to be considered in future studies. Inspired by Santero et al. (2011a), AzariJafari et al. (2016) investigated recent publications since 2011 to capture the latest development on the modeling of usually missing components such as pavement surface roughness, albedo effect, carbonation, etc. In addition, Inyim et al.

(2016) conducted a systematic review on 32 papers published between 1996 and 2015, with an attempt to reach a conclusion on the comparison of environmental sustainability between asphalt and concrete pavements. This study is distinct from the aforementioned ones in three ways. In contrast to previous reviews, which have focused on asphalt pavements (e.g. Wang et al., 2018) or alternative materials/construction technologies (e.g. Jamshidi et al., 2013), this study includes studies that cover a variety of LCA application areas. In addition, it covers the analysis period from 2003 to 2019, with 2017 to 2019 accounting for 34% of the publications. Therefore, this review offers an update on the most recent developments and applications of LCA in roads. Moreover, this study provides a new angle of understanding the use of LCA in roads by considering the nature of LCA and the unique characteristics of roads.

By conducting a critical review, this work aims to fulfill three objectives: 1) to draw a picture of the current methods and implementation of LCA in road projects from a life cycle point of view; 2) to identify the limitations and challenges of using LCA in the environmental assessment of roads; and 3) to point out future directions. The rest of this paper is organized as follows. Section 2 provides the research method for this review and Section 3 presents an overview on existing publications. Section 4 summarizes the main findings of this study, including the three fundamental LCA approaches and their applications in road projects. Section 5 discusses the limitations of existing studies and investigates future directions of LCA in road projects, and Section 6 concludes this review.

2 Research method

A six-step approach, based on Thomé et al. (2016), was adopted so that a systematic review could be conducted. A similar review process is also used by Wan et al. (2018). The first step was to define the review scope. The aim of this review was to investigate the development and implementation of the LCA approach in road projects. Therefore, all review activities were centered on this aim.

The second step was related to the identification of relevant articles through searching techniques, including the selection of databases and keywords. The Web of Science database was selected as the primary source because of its coverage and prime quality (Li et al., 2017). The searching terms, ("life cycle assessment" OR "LCA") AND ("road" OR "pavement") were used to identify articles that contain such keywords in the title, abstract, or keywords sections. Only peer-reviewed journal papers and reviews were selected based on quality considerations (Li et al., 2019). Other publication types, such as conference papers, theses, and letters were excluded.

Steps three and four were related to data collection and quality evaluation. Using the searching techniques mentioned above, 597 potentially relevant articles were identified, among which 220 are directly related to road or pavement LCA. It should be noted that roads are usually classified into three types of facilities, including earthwork zones, bridges, and tunnels (Park et al., 2016). Most studies are limited to the earthwork zone of paved roads. To ensure that the research aim was consistent, 21 studies on unpaved roads, embankments, and trenches, roundabout intersections, bridges, and tunnels were excluded in this review. The screening process is also adopted by Inyim et al. (2016) and Wan et al. (2018). As a result, a total of 199 peer-reviewed journal papers were retrieved.

The last two steps were data analysis and interpretation. Content analysis was selected as the method for data analysis because it was recommended as the best fit for analyzing textual data (Erlingsson and Brysiewicz, 2017). Table 1 presents the codes for the content analysis, including year, author, journal, location, goal of study, FU, system boundary, life cycle assessment method, data sources, impact category, major findings, and future needs. These codes were also aligned with the four-step LCA. For example, the FU and system boundary were related to the goal and scope definition.

Table 1. Codes for this review

Code	Description of the codes in this review
Year	Year of publication
Author	Authors of the publication
Publication venue	The journal where the paper is published
Location	The location where the research was conducted
Goal of study	The intended aim and objectives for carrying out the study
Functional unit (FU)	The reference unit for the assessment
System boundary	The phases and unit processes
Life cycle assessment method	The method for conducting the LCA
Data sources	The data sources
Impact category	The environmental concerns to which the LCI analysis results are assigned
Major findings	Main results that are related to the goal of the study
Future needs	Limitations or future directions identified by the authors of the publication

3 Overview of existing LCA studies on road projects

A preliminary analysis of the 199 selected papers published from 2003 to 2019 was conducted to provide descriptive information of these studies, including the publication years, journal distribution, and general classifications.

3.1 Publication distribution

Figure 1 illustrates the distributions of the publications. It shows that LCA on roads has attracted substantial research interest since 2012, which demonstrates the rising interest about this research area in the LCA community in recent years.

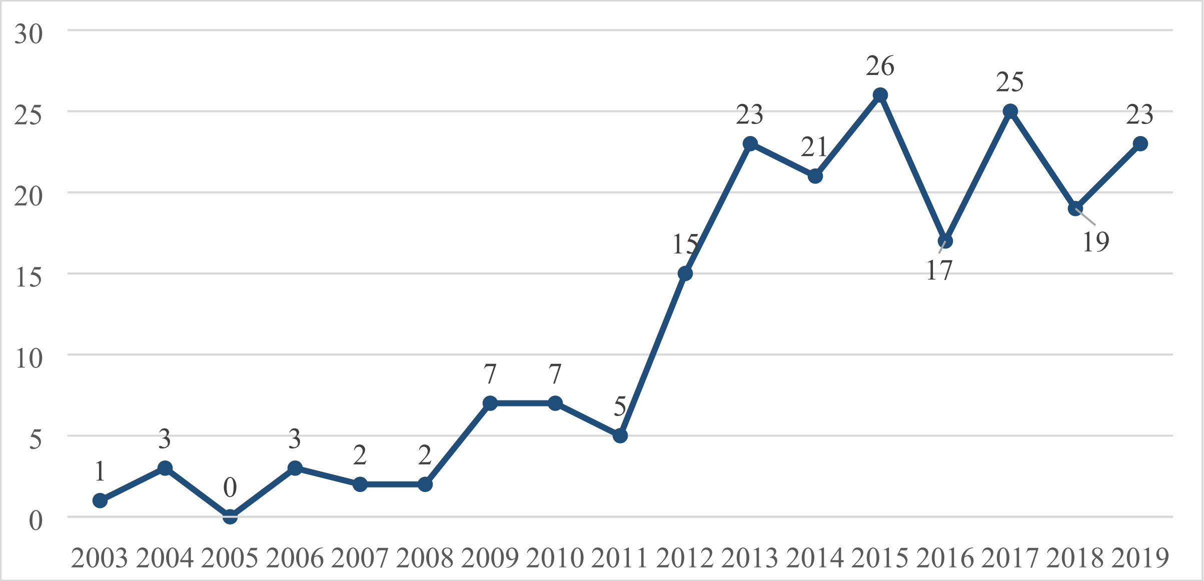

Figure 1. Distribution of retrieved publications by year

Appendix A illustrates the distribution of these articles in publication venues. In total, 50 journals have published relevant papers. Among these journals, the Journal of Cleaner Production has the highest number of publications (41), followed by Transportation Research Record: Journal of the Transportation Research Board and Transportation Research Part D: Transport and Environment, with 21 and 19 relevant articles, respectively.

3.2 General themes

In general, there were two main themes based on the goals, including the application of LCA in roads (113, 56.8%) and the modeling development of LCA in roads (77, 38.7%). Table 2 presents the description of these two main themes. In the application theme, the study goal was the application of LCA to evaluate roads or road materials, following the LCA processes defined in ISO 14044 (2006). Among these studies, 94 papers targeted the road structure, whereas the other 19 targeted the materials. In the modeling development theme, the study purpose was to develop an LCA tool for roads, or to introduce a method for calculating certain new impacts that were often excluded in previous studies (e.g., traffic delay and rolling resistance). Based on the research aim and objectives, the 94 papers focusing on the application of LCA in roads were targeted first. Table 2 and Figure 2 present the definition and distribution of themes, respectively, which show that the evaluation of materials is attracting immense research interest.

Table 2. Classification of the retrieved publications based on their goal of study

Classification		Description of the classifications	Publication
Typical application	Road evaluation	To evaluate the environmental impacts of a road project	26
	Alternative design	To compare different designs for a given road, such as rehabilitation methods, maintenance schemes, and various lifespan designs	19
	Material evaluation	To evaluate the environmental impacts of a material, such as a mixture, an additive, or an eco-friendly material (e.g., industrial by-products, recycled materials, and other modified materials)	51
	Material comparison	To compare different materials, such as concrete versus asphalt, and different asphalt products	17
Modelling development	Framework/tool development	To develop a framework or calculation tool for road evaluation	24
	LCC + LCCA	To develop a method that integrates LCA and lifecycle cost analysis (LCCA) in road evaluation	23
	New impacts	To develop a method to capture new impacts that are rarely considered in previous studies, including traffic congestion, albedo effects, rolling resistance, carbonation, noise, and lighting	30
Others		The goal of the study is not included in the above classifications	9

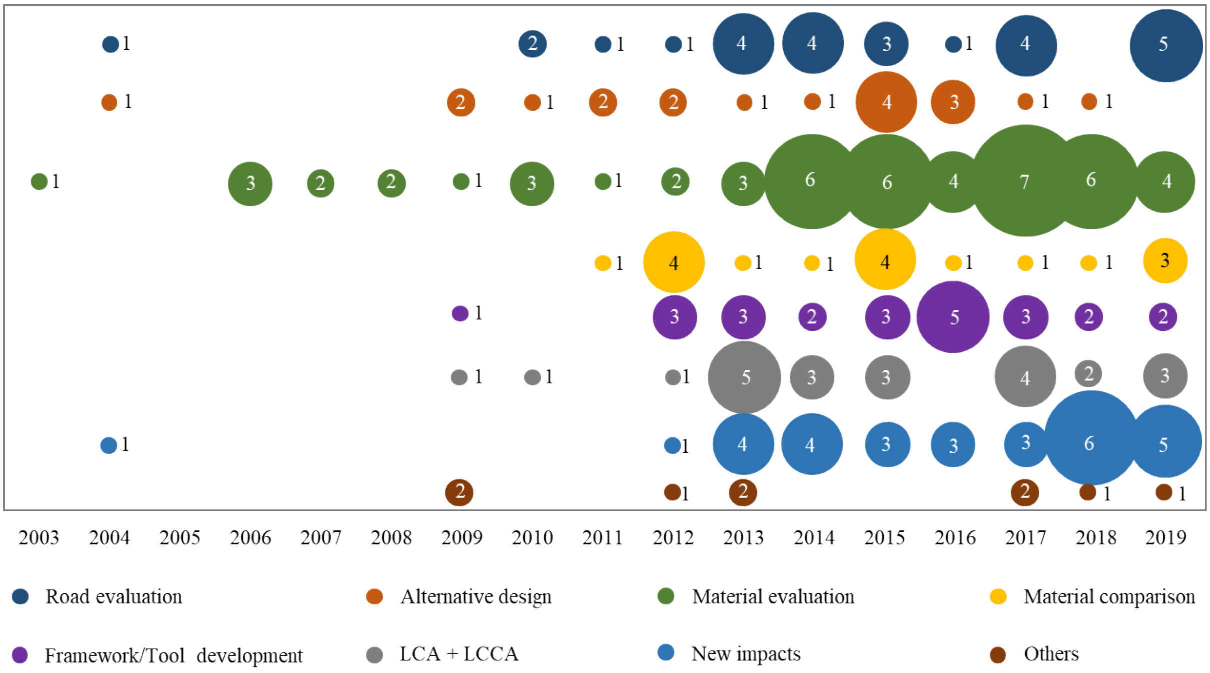

Figure 2. Distribution of publications by theme and year

4 Critical review of the approaches and applications of LCA in roads

In this section, the commonly used LCA approaches are compared and findings on the applications of LCA in roads are presented following the typical procedures of conducting an LCA study defined in ISO 14044 (2006).

4.1 LCA approaches

LCA is often categorized into process-based LCA (P-LCA), environmental input–output LCA (EIO-LCA), and hybrid LCA (Santos et al., 2017). P-LCA defines the system boundary by processes and divides the target system into a series of process flows to model the inputs and outputs of every process (Horvath and Hendrickson, 1998). It has been widely adopted in environmental evaluation of roads (e.g. Chiu et al., 2008; Chowdhury et al., 2010; Huang et al., 2009), with 67 (71.3%) studies using this method. However, this method requires data on consumption and environmental output to be obtained for every process, which is labor- and time-intensive. Therefore, P-LCA is often expensive and time-consuming, especially for a complex system that encompasses thousands of processes (Suh et al., 2004). It also has the risk of excluding a large number of inputs for upstream processes, which may have a significant effect on the total inventory (Choi et al., 2016).

To simplify the LCA and generate more comprehensive LCA results, EIO-LCA is proposed. In EIO-LCA, the boundary often spans the global economy, which includes the entire chain of suppliers (Suh et al., 2004). When producing the products in a sector, inputs, which are the outputs of other sectors, are required. Because each sector has environmental impacts per dollar of output, the overall environmental impacts can be quantified by summing up the products of the inputs and the environmental impacts of the corresponding sectors (Horvath and Hendrickson, 1998). Although EIO-LCA is able to improve the completeness of the traditional method, it faces problems such as the age of input–output data, homogeneity assumption, use of national average data, and high levels of sector aggregation (Choi et al., 2016; Hendrickson et al., 2006). As can be observed in Table 3, EIO-LCA has not been fully embraced, with only 6 studies conducted in the evaluation of roads (6.4%).

Hybrid LCA, which combines the two methods by using input–output (IO) data to complement the processes that are excluded in P-LCA, was later proposed (Bullard et al., 1978; Suh et al., 2004). The main advantage of this approach is that it improves the completeness of P-LCA while raising the reliability of EIO-LCA (Bullard et al., 1978). Table 3 summarizes the advantages and disadvantages of each method.

Table 3. Pros and cons of existing LCA methods

Comparison	Methods	Pros	Cons	Frequency
Process-based LCA (P-LCA)	• Identifies the input and output in each process of production of a product or service[1] • Provides assessment for specific processes[1]	• Can obtain detailed results for each process[1] • Has advantages when evaluating the use and EOL stages[2] • Allows comparison of specific products[2]	• Setting a system boundary is difficult[3] • "Cut-off" errors[1,3,4] • Unable to capture circularity effects[1] • Costly and time-consuming[1,3]	67 (71.3%)
EIO-LCA	• Provides an assessment of the whole economic system[1] • Quantifies interrelationships between various sectors of the economy[1]	• The analysis boundary is the whole economy; no "cut-off" errors[1] • Solves the problem of circularity effects[1] • Less costly and faster[1] • Reflects direct and indirect interactions between different economic sectors; provides both economic and sector-wide results[1]	• Unable to reflect particular processes owing to the heterogeneousness of sectors and the use of national average data[3] • Homogeneity and linearity assumptions[4] • Aged input–output data[3,4] • High levels of sector aggregation[3,4]	6 (6.4%)

Comparison	Methods	Pros	Cons	Frequency
Hybrid LCA	Usually combines the two methods by using IO data to complement the upstream processes, which are often excluded in traditional P-LCA[3]	• Overcomes the problem of the costly, time-consuming, or missing data of P-LCA[3,4,5] • Reduces “cut-off” errors of P-LCA and improves the consistency across the stages of the road life cycle[3,4,5] • Improves the reliability of EIO-LCA[3,4,5]	• Lack of standard methodological framework[5] • Lack of mature tool[5]	11 (11.7%)

Note:

[1] Hendrickson et al. (2006); [2] Choi et al. (2016); [3] Suh et al. (2004); [4] Bullard et al. (1978); [5] Crawford et al. (2018).

This table include 84 papers and the remaining 10 papers are not presented because their methods are not reported.

4.2 Current applications of LCA in roads

Complying with the ISO 14044 standard (ISO 14044, 2006), a typical LCA study often follows four steps: 1) defining goal and scope, clarifying system boundaries, and determining FUs; 2) compiling the life cycle inventory (LCI) by allocating the inputs (resources) and outputs (e.g., emissions) through the life cycle; 3) assessing the potential life cycle environmental impact of the target system (which is referred to as LCIA); and 4) interpreting the results from the LCIA for conclusions and recommendations. Each step will be investigated to examine the current common practices and identify limitations in existing studies so that future directions can be proposed accordingly for further improvement.

4.2.1 Goal and scope definition

4.2.1.1 The goal of the studies

The goal of LCA plays a vital role in defining the FU, setting the system boundary, and selecting data sources (Loijos et al., 2013). Existing LCA studies on roads are usually limited to four types of goals, namely, evaluating the environmental impact of roads, alternative designs, pavement materials, and alternative materials. In addition, the majority of the studies (89, 94.7%) were conducted based on a project-level analysis. Only a few have investigated the impacts of roads in a network context to inform policymaking at the network level. Therefore, the implications of these studies are limited to project level and can hardly benefit road planners or policy makers to achieve an optimal solution at a network or national level.

4.2.1.2 Functional unit (FU)

Like applying LCA in other sectors such as the buildings sector, various FUs were used in LCA studies on roads, making it difficult to compare results across studies (Anand and Amor, 2017; Säynäjoki et al., 2017). 68 studies (72.3%) used the road length, such as kilometer, lane-kilometer, and lane-mile. In addition, 11 papers (11.7%) used the treatment area, expressed for instance in square meters, as the FU where the scope of the study involved the surface or wearing course of the pavement. Another FU is the whole road project, which was usually used when evaluating the environmental impact of a specific strategy (e.g., road closure scheme during rehabilitation and emission control strategy) on a given road project. For example, Hanson and Noland (2015) compared the vehicle emissions when adopting various staging approaches for a rehabilitation project. Other studies have also used the volume (e.g., in cubic meters, cubic yards) to evaluate the impacts of earthworks or recycling of materials (e.g. Capony et al., 2013).

The use of these FUs has limitations. A lane mile or a square meter cannot be used as a standard FU (Cass and Mukherjee, 2011). It was pointed out by AzariJafari et al. (2016) that the information related to the road specifications should include region, lane width, shoulder width, thickness, roadway type, pavement type, and analysis period. It was argued that road functions could not be appropriately reflected if the FU did not include the roadway classification, lane width, and number of lanes into account. Appendix B presents the goals of the studies, together with the FUs of the twenty most cited papers and two recent highly cited publications with more than 10 citations (referred to as the 22 HCPs). It is found that a systematic presentation of such information was rarely adopted in existing studies.

In addition, it is reported that the missing consideration of the condition of pavement is also a shortfall in existing studies (Inyim et al., 2016). Unlike other products or services, the condition of a pavement often deteriorates over the long service life and it directly influences the function of a road. For example, the pavement roughness is an important indicator for the serviceability of a road (Al-Omari, 1994) and can cause up to 70% variation in the fuel consumption impacts caused by on-road vehicles (Batouli and Mostafavi, 2017). Therefore, an FU that integrates the changeable condition and performance of the pavement is required (Batouli and Mostafavi, 2017; Inyim et al., 2016).

4.2.1.3 System boundary

There are six phases during a road's life cycle, namely, materials extraction and production, materials transportation, construction, use, M&R, and EOL phases. The materials extraction and production stage usually includes the processes for manufacturing the road materials, from the acquisition of raw materials to final material production (i.e., mixing plant operations). The construction phase considers all preservation and construction activities, including the combustion of fuels of the paving equipment. It should be noted that materials transportation from manufacturing plants to construction sites may be integrated into the construction phase (e.g. Zhang et al., 2010) or treated as a separate phase (e.g. Kayo et al., 2015), depending on the specific aims of the studies. The M&R stage deals with three types of maintenance treatment, such as routine maintenance, preservation, and rehabilitation. In addition, EOL treatments include the demolition, debris transport, recycling, and final disposal at the end of a road's service life (Celauro et al., 2015). However, there is no common agreement on what to be included in the use phase. For example, Loijos et al. (2013) only considered the effects of albedo, carbonation, roughness, and lighting, and excluded the vehicle emissions. On the contrary, Treloar et al. (2004) not only included the vehicle emissions, but considered the manufacture, use, and maintenance of vehicles as well.

The materials extraction, transportation, and construction stages were the commonly included life cycle stages, with 91 (96.8%), 59 (62.8%), and 81 (86.2%), respectively. Meanwhile, the consideration of use, M&R, and EOL stages was less frequent, with 28 (29.8%), 55 (58.5%), and 32 (34.0%) studies. Table 4 presents the summary of work in the 22 HCPs. The EOL stage is usually excluded as the total demolition and disposal of an infrastructure is not common practice or is not allowed by the national maintenance policies (e.g., Italy) (Celauro et al., 2015). More importantly, the exclusion of the use stage from most of the existing studies is seen as a significant shortfall owing to its great global warming potential in roughness, structure, and albedo (Santero et al., 2011b). The omission is attributed to the limitations of the impact assessment method for the use phase and the common assumption that different roads generate the same impacts in this stage (Inyim et al., 2016).

Table 4. Summary of highly cited LCA studies in roads: system boundary

Studies	**System boundary**					
	Material production	Transportation	Construction	Use	M&R	EOL
Chiu et al. (2008)	√	√	×	×	√	×
Treloar et al. (2004)	√	×	√	√	√	×
Chowdhury et al. (2010)	√	×	×	×	×	×
Birgisdottir et al. (2006)	√	√	√	×	√	×
Birgisdottir et al. (2007)	√	√	√	×	√	×
Wang et al. (2012)	√	√	×	√	√	×
Huang et al. (2009)	√	√	×	×	√	×
Vidal et al. (2013)	√	√	√	√	√	√
Carpenter et al. (2007)	-	-	-	-	-	-
Cass and Mukherjee (2011)	√	×	√	×	×	×
Yu and Lu (2012)	√	×	√	√	√	√
Olsson et al. (2006)	√	√	√	√	×	×
Loijos et al. (2013)	√	×	√	√	√	√
Jullien et al. (2006)	√	-	√	×	×	×
Anastasiou et al. (2015)	√	√	√	×	√	√
Aurangzeb et al. (2014)	√	√	√	×	√	×
Oliver-Sola et al. (2009)	√	√	√	×	√	○
Roth and Eklund (2003)	-	-	-	-	-	-

Studies	System boundary					
	Material production	Transportation	Construction	Use	M&R	EOL
Tatari et al. (2012)	√	√	√	×	×	×
Giani et al. (2015)	√	√	√	×	√	√
Santos et al. (2017)	√	√	√	√	√	√
Farina et al. (2017)	√	×	√	×	√	×

Notes:

1. √ – included; ○ – limited consideration; - – not specified; × – not included;

2. Highly cited means twenty most cited papers and two recent highly cited publications with more than 10 citations.

4.2.2 Life cycle inventory (LCI)

4.2.2.1 LCI data sources

The choice of data sources can be a major decision in LCA studies (Martínez-Rocamora et al., 2016). The International EPD® System categorizes the data into three types for the LCI phase, i.e., primary, secondary, and tertiary data. Primary data refers to first-hand data usually obtained by on-site surveys and field investigations. Secondary data can be obtained in the literature, including published articles, annual environmental reports, and commercial databases. Tertiary data, or other generic data, is often available through statistical averages (Moretti et al., 2017).

Typically, an LCA study requires project (input) and emissions data. To obtain input data, primary data such as field investigation and interview with the contractors or equipment manufacturer are preferred (e.g. Cass and Mukherjee, 2011). However, first-hand data for material production and construction activities are not always complete (Gulotta et al., 2019). Therefore, secondary data are also a common source. For emissions data, primary data is extremely difficult to obtain and only Kang et al. (2014) and Al-Qadi et al. (2015) used self-developed local or regional database. For others, Ecoinvent, U.S. LCI databases, Athena database, and published literature are important sources for secondary data. The use of different sources can lead to distinct results even for the same product, compromising the comparability across studies. In addition, not all materials are included in the databases, especially recycled materials, which may lead to inaccuracy of the assessment results (dos Santos et al., 2017). Similar findings are also reported in the building LCA (Säynäjoki et al., 2017). More importantly, there were a significant number of studies (30, 31.9%) that did not report the data source, resulting in high uncertainty in the LCI results. Appendix C lists the data sources of the 22 HCPs.

4.2.2.2 LCA Tools

The selection of LCA tools is usually related to the adopted LCI method. Most of the papers that adopted the P-LCA method used SimaPro or GaBi software (e.g. Farina et al., 2017; Giani et al., 2015; Vidal et al., 2013). For EIO-LCA, the most commonly adopted tools are the Pavement Life-cycle Assessment Tool for Environmental and Economic Effects (PaLATE), which is a spreadsheet LCA and the LCCA program designed to assess the environmental and economic impacts of pavement and roads, and the Economic Input–Output Life Cycle Assessment (EIO-LCA) model, an online tool designed to make EIO-LCA method fast, easy to use, and free. For the hybrid LCA, however, there was no widely adopted tool, which may be one of the reasons that the hybrid approach is not widely used (Crawford et al., 2018). Unlike the building sector where the uncertainties aroused from the LCA tools have been widely discussed and highlighted (e.g. Emami et al., 2019), only dos Santos et al. (2017) conducted a comparative study on LCA tools for roads. It is concluded that results can vary significantly even when the same stages are considered with the same materials and equipment use. In addition, there are also 37 (39.4%) studies of which the tools are not reported. The analyst are recommend to be cautious in selecting LCA tool and improve their awareness to report the selection (dos Santos et al., 2017). Appendix C summarizes the LCA methods and tools in the 22 HCPs.

4.2.3 Life cycle impact assessment (LCIA)

4.2.3.1 LCIA methods

LCIA connects the LCI results to its environmental impacts by assigning the results to selected impact categories (ISO 14044, 2006). According to Van den Heede and De Belie (2012), there are two main schools of impact analysis methods. The first school is a damage-oriented method represented by Eco-indicator 99, which focuses on the endpoint environmental damages (where the actual environmental effects or damages occur), such as damage to ecosystem quality, damage to human health, and damage to mineral and fossil resources. The second one is considered to be a problem-oriented or midpoint method, and a representative example is CML 2001, for quantitative modeling within the early stages of the cause–effect chain. For example, a road's climate change effect can be calculated by an endpoint method to produce environmental damage to human health, or by a midpoint method (i.e. kilograms of CO2e). To offer users the choice of the level of results, methods that combine the midpoint and endpoint, such as ReCiPe, which is a fusion of CML 2001 and Eco-indicator 99, were also available.

In the existing literature, only 18 (19.1%) papers have reported the method of impact assessment. In these studies, many (17) adopted a midpoint method, including CML 2001 midpoint method (4 papers), ReCiPe midpoint method (8 papers), TRACI midpoint method (2 papers), and 3 other midpoint methods. The popularity of the ReCiPe may be attributed to the fact that it incorporated the widely used SimaPro software (Vidal et al., 2013), and it is convenient for having combined both assessment methods. Other publications, which did not report the method of impact assessment, commonly adopted midpoint methods for selecting midpoint impact categories, such as global warming potential, acidification, and eutrophication, to name a few. Similar preference for the midpoint approach is also reported in other sectors (e.g. Yi et al., 2014). Main reasons are that the endpoint approach requires a high level of expertise and is exposed to much higher uncertainty than the midpoint approach. Nevertheless, the midpoint approach may not provide the results that decision makers really expect (Bare et al., 2000). Therefore, Bare et al. (2000) suggested that a consistent framework is needed to present both sets of results, either in a combined or parallel approach.

4.2.3.2 LCIA

Selecting impact categories and conducting the impact assessment are mandatory elements of an LCA study (ISO 14044, 2006). However, it should be noted that there is a lack of a standardized way of reporting the results.

Many studies offer simple quantification of the outputs without impact assessment. For instance, Cass and Mukherjee (2011) calculated the greenhouse gas (GHG) emissions for highway construction without conducting a further impact assessment. Such omission of the impact assessment step can introduce difficulty in the decision-making process because the simple estimation of gas emissions cannot provide intuitive information (Inyim et al., 2016). A similar limitation can also be found in comparison studies, such as in Yu and Lu (2012). However, an LCI study alone is not supposed to be used for comparative assertions (ISO 14044, 2006).

Other studies, as can be observed in Appendix C, attempted to interpret the results using impact assessment, but they selected extremely varied impact categories, making it difficult to conduct a cross comparison between different studies. Among these studies, GHG emissions and energy consumption were the most consistently used assessment metrics. Other widely used categories also included damage to the ecosystem and human health. Little consideration has been given to natural resources such as land use.

It is also found that few authors explained the reasons for choosing certain impact categories, thus not clarifying whether the selection was consistent with the goal and scope of the study. For example, Santos et al. (2015) adopted eight impact categories, whereas Santos et al. (2017) only considered four categories without providing reasons for including or excluding certain impacts. Out of these studies, only two studies, i.e., Fitch et al. (2013) and Veran-Leigh et al. (2019), elaborated the reasons for selecting each impact category.

4.2.4 Life cycle interpretation

Life cycle interpretation comprises three components, that is, identifying significant issues, checking completeness, consistency, and sensitivity, and drawing conclusions and recommendations (ISO 14044, 2006).

4.2.4.1 Phase/Process

Each stage in the life cycle of a road contributes differently to its environmental impacts. As can be observed from Appendix D, the material extraction and production stage was identified as the main contributor to the total carbon emissions and energy consumption by most studies. In this stage, the cement production process has been highlighted as the main contributor (e.g. Choi et al., 2016; Loijos et al., 2013; Oliver-Sola et al., 2009; Weiland and Muench, 2010). Current studies also pointed out the importance of the use phase (e.g. Chen et al., 2016). According to Araujo et al. (2014), the impact of the use phase on the environment was approximately 700 times higher than that of the construction phase. The use phase also dominates the environmental performance for roads with high traffic volumes (Santos et al., 2015).

4.2.4.2 Asphalt vs concrete pavement

The comparison of pavement materials such as asphalt and concrete has attracted much research attention over these years, although no general conclusion has been drawn. For example, Weiland and Muench (2010) and Yu and Lu (2012) both investigated rehabilitation alternatives. The former argued that the hot mixed asphalt pavement (HMA) had a higher energy use and the Portland cement concrete (PCC) had a higher global warming potential (GWP); the latter drew the conclusion that PCC was better than HMA in both energy use and GWP performance. A possible reason for the different results could be the overlook of impacts from the use phase and EOL phase by Weiland and Muench (2010), whereas Yu and Lu (2012) considered the whole life cycle, except for the transportation of materials. More widely agreed results may be that the asphalt pavement could offer a reduction in GWP but concrete has an advantage in pavement energy demand (e.g. Dumitrescu et al., 2014; Gschosser and Wallbaum, 2013; Gschosser et al., 2012; Weiland and Muench, 2010). It should also be noted that most studies had no or had limited consideration of the use phase, except Yu and Lu (2012), which might influence the results.

4.2.4.3 Impact of eco-friendly technologies

The reclaimed asphalt pavement (RAP) and warm mix asphalt (WMA) were the commonly investigated eco-friendly technologies in current studies. RAP allowed a reduction of the use of virgin materials and WMA was used to lower the production temperature of the asphalt mixture (Giani et al., 2015). Using RAP could have a significant potential of reducing eco burdens of both rehabilitation (Chiu et al., 2008; Turk et al., 2016) and initial construction projects (Aurangzeb and Al-Qadi, 2014; Aurangzeb et al., 2014), especially when combined with HMA (Giani et al., 2015; Vidal et al., 2013). However, the studies provided contrasting results related to the impacts of using a high content of RAP. Aurangzeb and Al-Qadi (2014) and Aurangzeb et al. (2014) proved that reductions of energy and GHG could increase with an increase of RAP content to 30%, 40%, and 50%. On the contrary, Saeedzadeh et al. (2018) reached the opposite conclusion that high RAP content could lead to higher environmental burdens. As for WMA, Liu et al. (2014) and Mazumder et al. (2016) indicated that WMA was more beneficial to the environment than HMA. On the contrary, Tatari et al. (2012), Vidal et al. (2013), and Anthonissen et al. (2015) argued that this was not necessarily true because of the significant influence of additives, especially the synthetic zeolites.

4.2.4.4 Sensitivity and uncertainty analysis

A sensitivity analysis is a compulsory element in the life cycle interpretation phase by estimating the effects of a chosen method or data on the LCA results. The aim is to evaluate the reliability of the final results by quantifying the extent to which the results are affected by uncertainties coming from data, allocation methods, or LCIA calculation. The uncertainty analysis is often used as a supplement and is supposed to quantify uncertainties, such as model inaccuracy, input uncertainty, and data variability (ISO 14044, 2006). However, limited studies have reported such results, indicating high uncertainties in the results. In total, 32 studies (34.0%) conducted a sensitivity analysis, usually on the effects of transport management and traffic growth (e.g. Mendoza et al., 2012; Yu and Lu, 2012). In addition, only 17 studies (18.1%) conducted an uncertainty analysis. In these studies, only a few complied with the requirement of ISO 14044 (2006) that sensitivity analysis is mandatory and uncertainty analysis should supplement the results. For example, Wang et al. (2012) implemented a sensitivity analysis without clearly reporting the results. Giani et al. (2015) implemented a separate uncertainty analysis without conducting a sensitivity analysis. This may suggest a need for a clearer definition and guidance of the sensitivity and uncertainty analyses based on the ISO 14044 (2006) standard.

5 Discussion and recommendations

Based on the findings and the future needs identified in existing studies, this section discusses the main limitations in LCA applications in roads and make recommendations for future directions accordingly.

ISO 14044 (2006) provides a general framework and guideline for LCA, but the challenges of selecting FUs, defining system boundaries, and mining data for a specific field are left to the researchers based on their own discretion (Loijos et al., 2013). As can be observed from the findings of this review, several limitations can be found the LCA in existing studies.

- **Goal and scope definition**

  Mostly project-oriented research. Over 90% of the existing papers are project oriented and very few investigate the impacts of roads in a network context, limiting the value for policy makers, such as road authorities (Zhang et al., 2013). The cumulative emissions of the road network of a region/nation remain unclear and it is difficult to capture the regional disparities of the emissions under the existing LCA framework (Chen et al., 2017). Therefore, region-specific strategies for reducing the emissions are difficult to be developed. Another limitation of the project-level LCA is that road maintenance works are often planned in isolation to achieve an optimal solution for the project (Galatioto et al., 2015). The decision level at the network level, as Santos et al. (2017a) and Santos et al. (2018) have suggested, is much more complicated with budget consideration. It is therefore recommended that future research needs to consider the road network as a whole so that useful implications can be drawn for policymaking.

  Inconsistent selection and definition of FU. There are various FUs being used by existing studies which makes it difficult to make comparison between studies. To improve the comparability across studies, the consistency of the use of FUs needs to be increased (Inyim et al., 2016). In addition, currently used FUs are considered insufficient to reflect the changing functions of a road. It is therefore recommended that the definition of FU should consider the evolving road performance so that the real time function of roads can be reflected (Batouli and Mostafavi, 2017).

Lack of consideration of post construction stages. The use and M & R phases can have significant environmental impacts (Santero and Horvath, 2009; Wu et al., 2014). However, only a few studies have included these phases. There is still a lack of a method to accurately decide the maintenance measures for the whole life cycle of a road due to the constantly changing circumstances. In addition, the impact sources of the use phase are not consistently defined and methods for this phase is insufficiently developed. Future studies are recommended to fully capture these phases so that reliable outcomes can be delivered (Inyim et al., 2016). Furthermore, unlike common products, roads can receive rehabilitation over and over again and therefore may not have a clear life cycle. This suggests a need to further discuss the life cycle of a road and whether or how the EOL stage should be included in a typical LCA study (Batouli and Mostafavi, 2017).

- **LCI:**

Limited report of data sources and LCA tools. Different databases and LCA tools are being used in existing studies, which can lead to distinct results even for the same product or processes (dos Santos et al., 2017). However, most authors are not aware of the uncertainty and do not report the data sources and LCA tools. Future studies are recommended to consider such uncertainty in sensitivity and uncertainty analysis (Emami et al., 2019). There is also a need for studies that compare the results generated from different data sources or LCA tools to reveal uncertainties introduced from data and tools can be revealed.

- **LCIA:**

Lack of standardized LCIA procedure. Missing impact assessment phase, limited report of LCIA method and an inconsistent selection of impact categories are identified for the LCIA step, which result in difficulties in conducting comparisons across existing work (Inyim et al., 2016). A standardized LCIA procedure is therefore needed to improve the awareness of the LCIA step and guide the selection of LCIA method and impact categories.

- **Life cycle interpretation:**

  Lack of sensitivity and uncertainty analysis. A large amount of uncertainty exists for an LCA study, including parameter (input) and data uncertainty in the LCI step and method uncertainty in the LCIA step (Bare et al., 2000). The low awareness and lack of sensitivity and uncertainty considerations indicate high uncertainties on results delivered by existing publications. Future studies should conduct such analyses in order to ensure the reliability of their results.

As can be seen from the discussion, a lack of consistency and standardization is identified in each step, which echoes the key findings of AzariJafari et al. (2016), Inyim et al. (2016), and Santero et al. (2011b). Those limitations are considered to be rooted in the incompatibility of conventional LCA method and the characteristics of roads, meaning that the ISO 14044 is not perfectly suitable for guiding the LCA applications in roads (Batouli and Mostafavi, 2017; Cass and Mukherjee, 2011). There is therefore a need to standardize the LCA approach specifically for roads in future research.

In addition, from the review, it is found that the time effect has not been well captured in existing LCA studies on roads. For example, in current practice, it is common to simply aggregate the emissions generated at different times within the life cycle without discounting the values as the LCCA studies usually do (e.g. Cass and Mukherjee, 2011; Chiu et al., 2008;

Hanson and Noland, 2015; Yu and Lu, 2012; Yu et al., 2018). The aggregated LCI results are usually interpreted to potential environmental impacts through LCIA and adopted directly for decision making, which can cause several problems. First, it is difficult to compare two road designs with different service life. Second, the global warming impact of a GHG decreases with time and the GWP value, which evaluates such impact, is very sensitive to the time horizon (Levasseur et al., 2010), and cannot be reflected by an aggregated value. More importantly, the aggregated value masks the temporal distribution of emissions along the life cycle (Yu et al., 2018). As a result, one project with low emissions at the construction phase and high emissions at the use phase may have the same LCI results as another that has a completely different emission distribution. Such practice creates difficulties in determining which project is more sustainable if the dynamic changes of the environmental impacts of emissions are not considered. Among the studies, only one study, i.e., Yu et al. (2018), has considered this effect. Therefore, taking into account the time effect should be an imperative improvement area for future studies.

6 Conclusion

LCA has been widely adopted to evaluate the environmental impacts of roads so that sustainable practices in the life cycle stages of the road, including materials extraction, transportation, construction, operation, maintenance, and EOL treatments, can be adopted. Over the past two decades, a large number of LCA studies have been conducted in road projects and a complete review of these studies is conducted. It is found that there are two general themes in the existing studies, which are the application of LCA in roads and the modeling development of LCA. Among all the application themes, P-LCA is the most commonly adopted approach. In addition, most of the current applications have a project-oriented goal of study. They are also found to be inconsistent in terms of selection of FU, lack of consideration of the

M&R, use, and EOL phases, high uncertainty due to limited report on data sources, sensitivity and uncertainty analyses, and lacking a standardized way of conducting impact assessment.

The consequences of these inconsistencies are also investigated. First, project-level studies have limited implications for policymaking. Second, the non-standardized procedure of conducting LCAs in roads is hindering their further development and implementation. Third, existing studies fail to consider the time effect of the environmental impact evaluation, causing difficulties in decision making between alternative road designs, which usually have a long life span. Therefore, it is recommended that future studies pay more attention to the network-level analysis and further standardize and tailor the LCA methods to align them with the characteristics of roads. Taking the dynamic changes in the environmental impacts of emissions into consideration in road LCA has also been highlighted for future work. Improvements in these areas can fill the existing knowledge gap and generate more reliable results to better inform both policymaking and decision making in the area of advancing the sustainability of roads.

7 Acknowledgments

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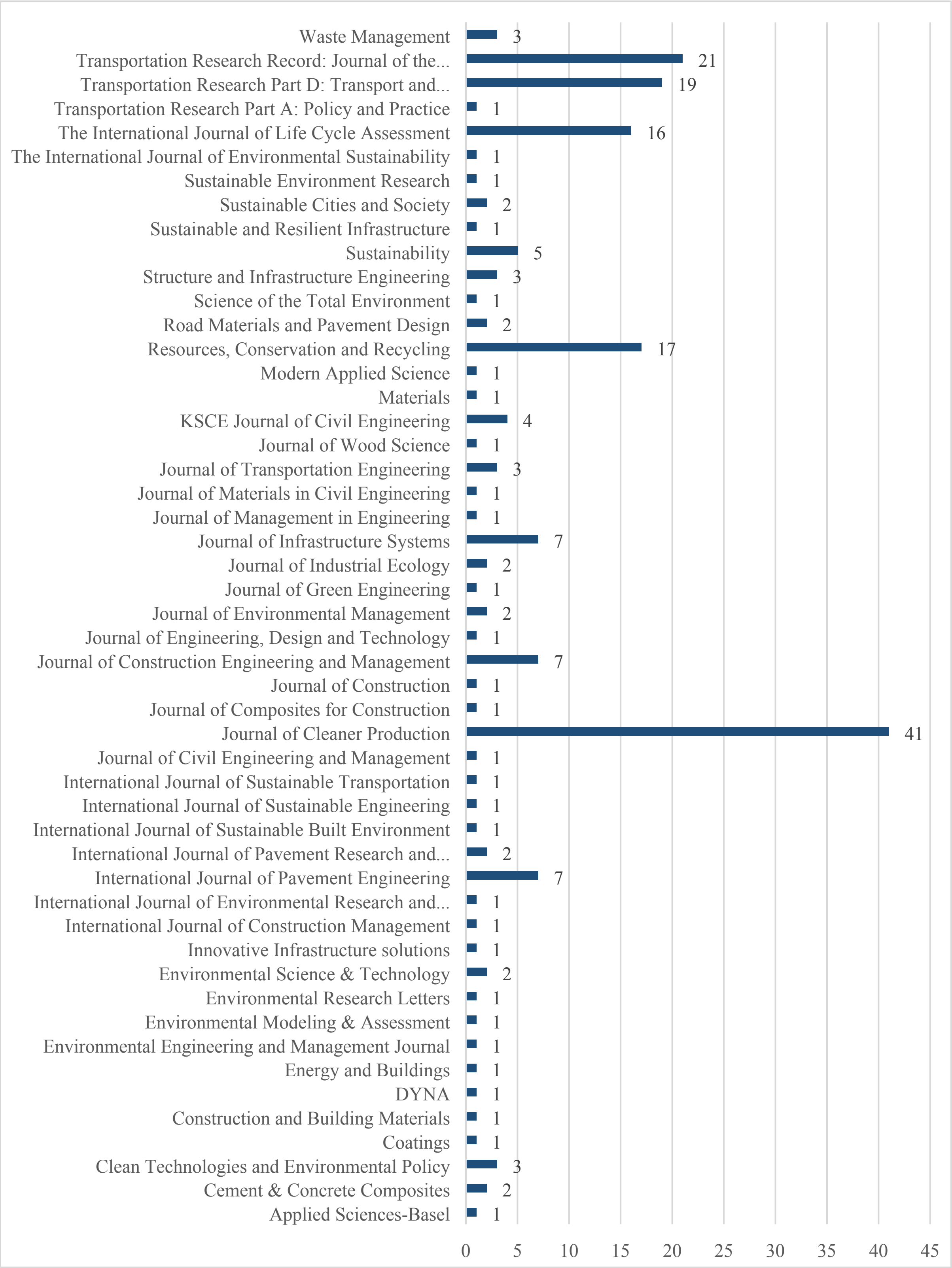
Appendix A. Distribution of retrieved publications by journal



Appendix B. Summary of highly cited LCA studies in roads: goal of study and functional parameters

Citation	Studies	Goal of study	Location	Functional unit (FU)	Roadway classification	Lane width	Shoulder width	Layers & Thickness	Lanes type and number	Analysis Period
67	Chiu et al. (2008)	Material evaluation	China (Taiwan)	Length: per lane-kilometer	-	2.65 m	-	5 cm	Asphalt, 1	40 years
58	Treloar et al. (2004)	Road evaluation	Australia	Length: 5 km	Rural roads	-	-	-	Various, -	40 years, 20 years
53	Chowdhury et al. (2010)	Material evaluation	US	Length: 1 km	-	2.5 m	-	600 mm	-, -	-
53	Birgisdottir et al. (2006)	Material evaluation	Denmark	Length: 1 km	Secondary road	3.5 m	2.1 m	0.7 m in total	Asphalt, 2	100 years
53	Birgisdottir et al. (2007)	Material evaluation	Denmark	Length: 1 km	Secondary road	7 m in total	-	0.37 m	Asphalt, -	100 years
52	Wang et al. (2012)	Alternative design	US	-	Rural road	-	-	-	Both asphalt and concrete, -	-

Citation	Studies	Goal of study	Location	Functional unit (FU)	Roadway classification	Lane width	Shoulder width	Layers & Thickness	Lanes type and number	Analysis Period
50	Huang et al. (2009)	Alternative design	UK	Length: 2.6 km	-	3.5 m	-	200 mm base; 60 mm binder course; 40/50 mm layer	Asphalt, 2	-
50	Vidal et al. (2013)	Material evaluation	Spain	Length: 1 km	1000 vehicles per day (8% heavy vehicles)	13 m	-	0.08 m asphalt layer	Asphalt, 2	40 years
45	Carpenter et al. (2007)	Material evaluation	US	Length: 305 m	Highway	10.4 m	1.5 m	Various	Asphalt, -	-
44	Cass and Mukherjee (2011)	Road evaluation	US	Length: per lane mile	Highway	24 feet	-	-	Concrete, 4	-
39	Yu and Lu (2012)	Alternative design	US	Length: one km overlay system	Highway	3.6 m	1.2 m, 2.7 m	225 mm PCC surface; 250 mm base course	Various, 2*2	40 years

Citation	Studies	Goal of study	Location	Functional unit (FU)	Roadway classification	Lane width	Shoulder width	Layers & Thickness	Lanes type and number	Analysis Period
31	Olsson et al. (2006)	Material evaluation	Sweden	Length: 1 km road	-	-	-	-	-, -	-
29	Loijos et al. (2013)	Road evaluation	US	Various	Various	Various	Various	Various	Concrete, various	40 years
29	Jullien et al. (2006)	Material evaluation	France	Area: a 3.8 m * 150 m road section	-	3.8 m	-	0.07 m	Asphalt, -	-
28	Anastasiou et al. (2015)	Material comparison	Greece	Length: 1 km	Urban road (low traffic)	7.3 m in total	-	-	Concrete, 2	40 years
28	Aurangzeb et al. (2014)	Material evaluation	US	Length: a 1.6 km lane	-	-	1.8 m	254 mm binder course; 51 mm surface course	Asphalt, 1	45 years
28	Oliver-Sola et al. (2009)	Alternative design	Spain	Area: 1 m^2 of sidewalk	Urban	-	-	All layers	Concrete, -	45 years
26	Roth and Eklund (2003)	Material evaluation	Sweden	-	-	-	-	-	-, -	-

Citation	Studies	Goal of study	Location	Functional unit (FU)	Roadway classification	Lane width	Shoulder width	Layers & Thickness	Lanes type and number	Analysis Period
25	Tatari et al. (2012)	Material comparison	US	Length: 1 km	-	7.2 m (total)	-	Different asphalt surface layer; 10 in. base course layer	Asphalt, 2	30 years
23	Giani et al. (2015)	Material evaluation	Italy	Length: 1 km	Suburban road	15 m (total)	-	25 cm	Asphalt, 2 * 2	30 years
13	Santos et al. (2017)	Material evaluation	US	Length: 1 km	Highway	3.66 m	-	-	Asphalt, 2	50 years
11	Farina et al. (2017)	Material evaluation	-	Length: 1 m of built pavement layer	-	Depending on the project	-	Depending on the project	Asphalt, -	18 years, 20 years

Notes:

1. - – not specified;

2. Highly cited means twenty most cited papers and two recent highly cited publications with more than 10 citations.

Appendix C. Highly cited LCA studies in roads: LCI method, database and tool, impact categories, and sensitivity and uncertainty analysis

Studies	Method	Data sources	Tool	Output/Impact categories	Sensitivity	Uncertainty
Wang et al. (2012)	Combined models	Stripple (1998); Athena Institute (2006); EcoInvent; USLCI; Cement LCI by PCA	-	Energy use, Greenhouse gas (GHG) emissions	√	√
Birgisdottir et al. (2006)	P-LCA	Standard sources, i.e., Stripple (2001); Environmental Design of Industrial Products database	ROAD-RES model	Leaching of heavy metals and salts from the bottom ash, Resource and energy consumption, Emissions (CO_2, NO_x), Salts used for road salting	×	×
Vidal et al. (2013)	P-LCA	Field study; Ecoinvent; Published literature	SimaPro	All 18 ReCipe Midpoint impact categories; 3 ReCipe endpoint damage categories; cumulative energy demand	×	√
Giani et al. (2015)	P-LCA	Key processes: Company survey; Upstream processes: Ecoinvent database; published literature	SimaPro 7.3	All 18 ReCipe Midpoint impact categories	×	√
Oliver-Sola et al. (2009)	P-LCA	Ecoinvent 1.2 database	EcoConcrete LCA tool	Abiotic depletion potential, Acidification potential, Eutrophication potential, Global warming potential (GWP), Human toxicity potential, Ozone layer depletion potential, Photochemical ozone creation potential	×	√

Studies	**Method**	**Data sources**	**Tool**	**Output/Impact categories**	**Sensitivity**	**Uncertainty**
Chiu et al. (2008)	P-LCA	Eco-indicator 99	-	Energy sources, Resources	×	×
Chowdhury et al. (2010)	P-LCA	Published literature; CMLCA	CMLCA	Acidification potential, Aquatic ecotoxicity potential, Aquatic sediment ecotoxicity potential, Energy consumption, GWP, Human toxicity potential, Terrestrial ecotoxicity potential	×	×
Huang et al. (2009)	P-LCA	Published literature and publications	VISSIM, EnvPro	Acidification, Eco-toxicity, Eutrophication, Global warming, Human toxicity, Photo-oxidant formation	×	×
Loijos et al. (2013)	P-LCA	Published literature and LCI databases	-	GWP	√	×
Yu and Lu (2012)	P-LCA	Portland Cement Association; Swedish Environmental Research Institute	-	Energy (Primary and feedstock), GHG (CO_2, CH_4, N_2O, VOC, NO_x, CO, PM_{10}, SO_x)	√	√
Birgisdottir et al. (2007)	P-LCA	-	ROAD-RES model	Acidification, Ecotoxicity in water/soil, Global Warming, Human Toxicity via air/water/soil, Nutrient Enrichment, Photochemical Ozone Formation, Stored Ecotoxicity to water/soil, Stratospheric Ozone Depletion	√	×

Studies	Method	Data sources	Tool	Output/Impact categories	Sensitivity	Uncertainty
Olsson et al. (2006)	P-LCA	-	-	Emissions to air (SO_2, NO_x, CO, CO_2, HC, CH_4, VOC, N_2O, and particles) and water (COD, N-tot, Oil, Phenol, As, Cd, Cr, Cu, Ni, Pb, and Zn), Resources use (natural aggregates, energy)	√	×
Jullien et al. (2006)	P-LCA	-	-	Odors, PAH, VOC	×	×
Anastasiou et al. (2015)	P-LCA	-	SimaPro 7.1	GWP_{100}, Resource use	√	×
Farina et al. (2017)	P-LCA	-	SimaPro 7.3	17 ReCiPe midpoint categories; 3 ReCiPe endpoint damage categories	×	×
Cass and Mukherjee (2011)	Hybrid	Site investigation using FieldManager	SimaPro 7, EIO-LCA, e-CALC	CO_2 emissions	×	×
Tatari et al. (2012)	Hybrid	Published literature and report; National Renewable Energy Laboratory LCI database	-	CH_4, CO, CO_2, N_2O, PM, SO_2, Cumulative mass, Ecological cumulative exergy consumption, Energy, Industrial cumulative exergy consumption	√	√

Studies	Method	Data sources	Tool	Output/Impact categories	Sensitivity	Uncertainty
Treloar et al. (2004)	Hybrid	Published literature	-	Energy	×	×
Aurangzeb et al. (2014)	Hybrid	-	-	Energy consumption, GHG emissions (CH_4, CO_2, N_2O)	×	×
Santos et al. (2017)	Hybrid	-	EIO-LCA model	Acidification air (AC), Eutrophication air (EU), Human health criteria pollutants (HH), Photochemical smog formation (PSF)	√	√
Roth and Eklund (2003)	-	-	-	-	×	×
Carpenter et al. (2007)	-	-	PaLATE, HYDRUS2D	CO, CO_2, NO_X, PM_{10}, SO_2, Energy, Hg, HTP (Cancer), HTP (Non-cancer), Pb, RCRA HazW Gen, Water	×	×

Notes:

1. - – not specified; √ – included; × – not included;

2. Highly cited means twenty most cited papers and two recent highly cited publications with more than 10 citations.

Appendix D. Overview of key findings on the contributions of different life cycle phases

		Phases						Analysis	
Studies	**Location**	Material production	Transportation	Construction	Use	M&R	EOL	**Period (years)**	**Results**
Cass and Mukherjee (2011)	US	√	×	√	×	×	×	-	**Materials, equipment, and fuel production**: 90%–94% of the CO_2 emissions; Equipment use and transportation: 6–10%
Santos et al. (2015)	Portugal	√	√	√	√	√	√	40	**Materials and usage phases**: major contribution to overall environmental impacts (low-volume traffic roads: materials phase contributes the most; high-volume traffic roads: usage phase dominates)
Loijos et al. (2013)	US	√	×	√	○	√	√	40	Year one generates the **majority of emissions** (materials production, pavement construction)
Kayo et al. (2015)	Japan	√	√	√	×	×	×	-	**Raw material procurement** - 88%; Material production - 7%; Transportation - < 1%; Construction: 4%
Kang et al. (2014)	US	√	√	√	×	×	×	-	The energy consumption and GWP in the **material phase** is remarkably higher than in the construction phase.
Mendoza et al. (2012)	Spain	√	×	√	×	×	√	> 45	**Construction materials** have the highest environmental impact (48–87%)

				Phases				**Analysis**	
Oliver-Sola et al. (2009)	Spain	√	√	√	×	√	○	45	Main contributor: **cement production** (especially clinker)
Weiland and Muench (2010)	US	√	√	√	×	√	×	50	**Material production** (cement, asphalt, HMA, PCC) dominates all impact categories
Yu and Lu (2012)	US	√	×	√	√	√	√	40	**Materials, congestion, and usage** contribute the most to air emissions and energy consumptions
Chen et al. (2016)	US	√	×	√	√	√	√	20, 40	**Material module, usage module**: two dominators
Choi et al. (2016)	US	√	√	√	×	√	√	50	**Cement manufacturing:** top-contributing sector
Mazumder et al. (2016)	US	√	√	√	√	√	×	50	**Material phase**: 97% of overall human toxicity in water (asphalt)
Araujo et al. (2014)	-	√	×	√	√	√	√	20	The energy consumption of the **use stage** is about 700 times higher than that of the construction phase

Notes:

1. √ – included; ○ – limited consideration; - – not specified; × – not included;

2. Highly cited means twenty most cited papers and two recent highly cited publications with more than 10 citations.

Declarations of interest: None.

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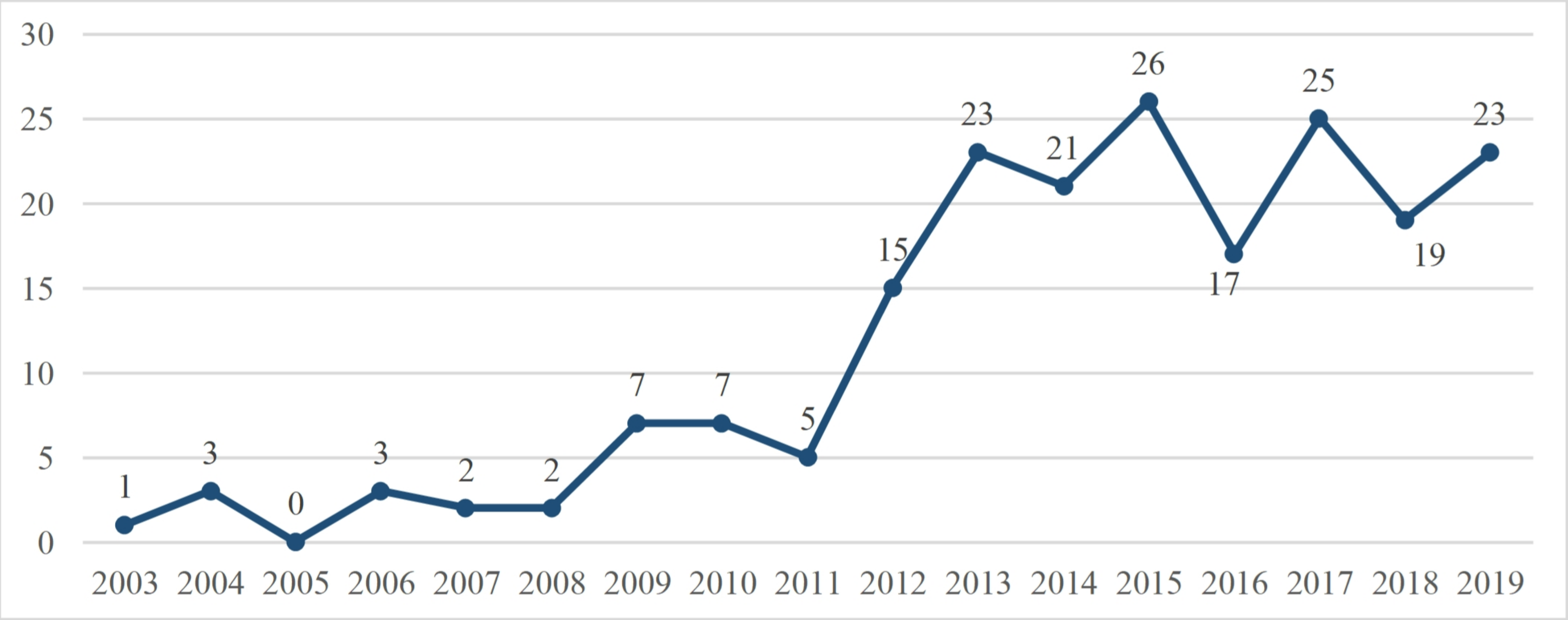
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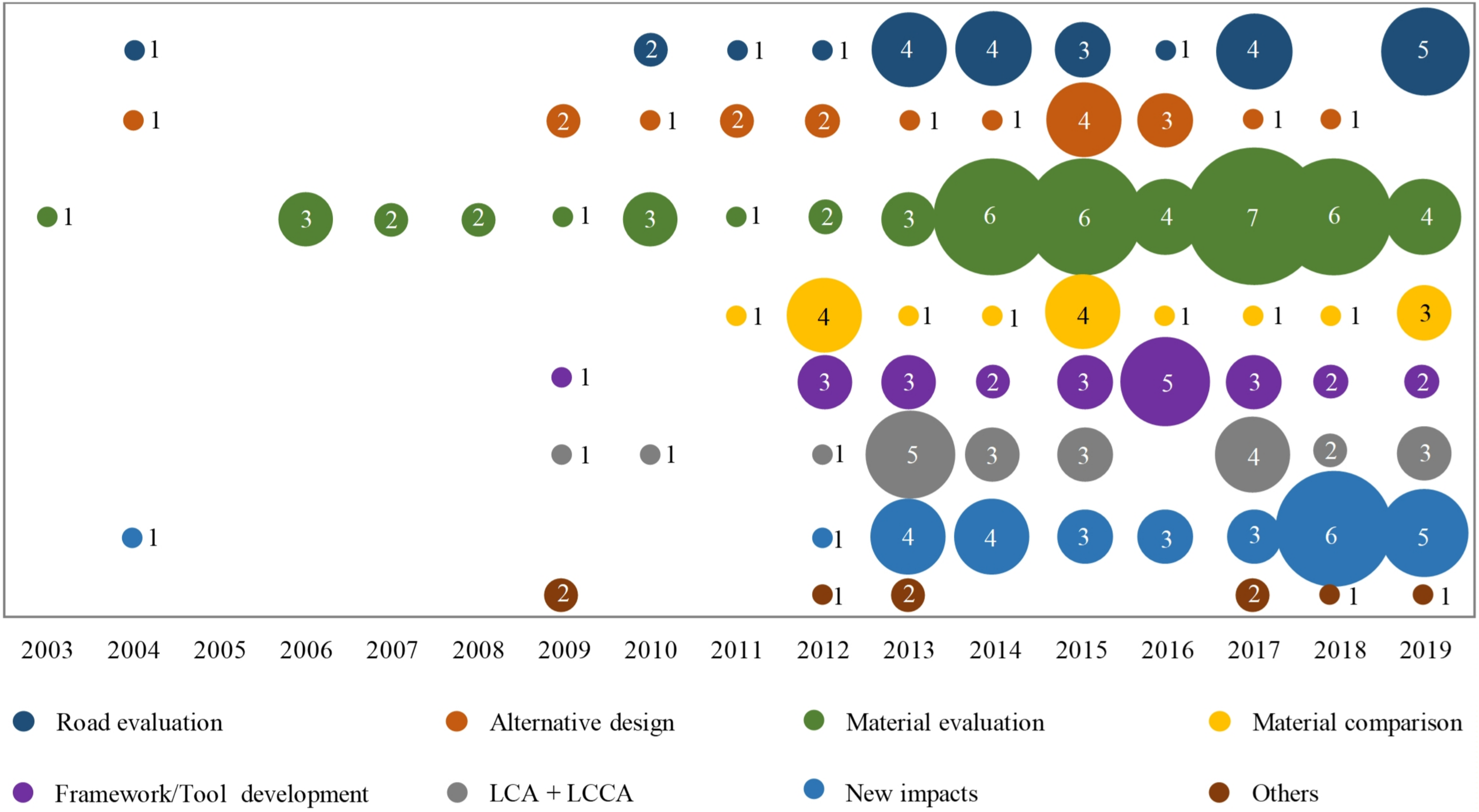
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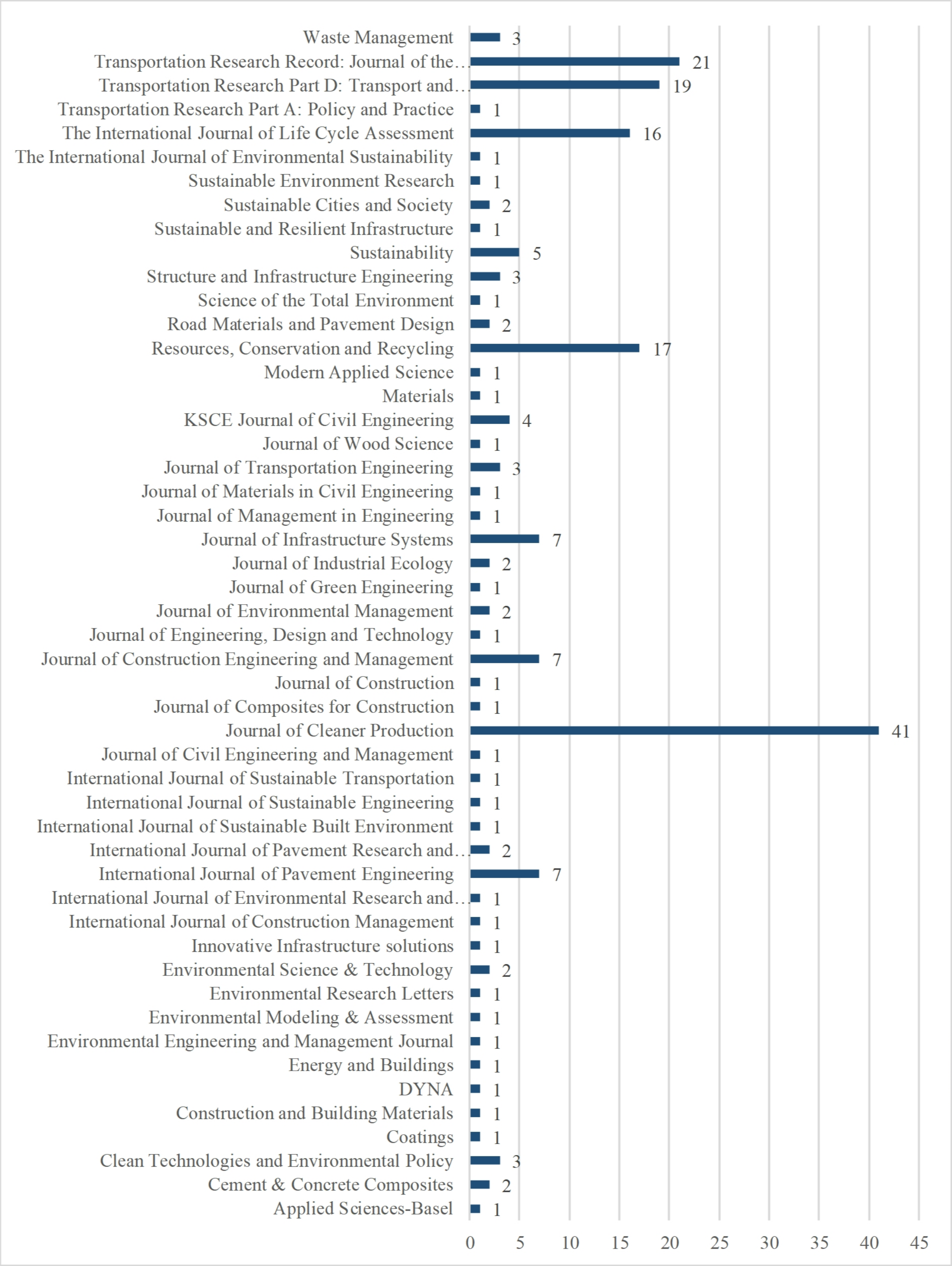
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Transportation Research Record: Journal of the… 21
Transportation Research Part D: Transport and… 19
Transportation Research Part A: Policy and Practice 1
The International Journal of Life Cycle Assessment 16
The International Journal of Environmental Sustainability 1
Sustainable Environment Research 1
Sustainable Cities and Society 2
Sustainable and Resilient Infrastructure 1
Sustainability 5
Structure and Infrastructure Engineering 3
Science of the Total Environment 1
Road Materials and Pavement Design 2
Resources, Conservation and Recycling 17
Modern Applied Science 1
Materials 1
KSCE Journal of Civil Engineering 4
Journal of Wood Science 1
Journal of Transportation Engineering 3
Journal of Materials in Civil Engineering 1
Journal of Management in Engineering 1
Journal of Infrastructure Systems 7
Journal of Industrial Ecology 2
Journal of Green Engineering 1
Journal of Environmental Management 2
Journal of Engineering, Design and Technology 1
Journal of Construction Engineering and Management 7
Journal of Construction 1
Journal of Composites for Construction 1
Journal of Cleaner Production 41
Journal of Civil Engineering and Management 1
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International Journal of Environmental Research and… 1
International Journal of Construction Management 1
Innovative Infrastructure solutions 1
Environmental Science & Technology 2
Environmental Research Letters 1
Environmental Modeling & Assessment 1
Environmental Engineering and Management Journal 1
Energy and Buildings 1
DYNA 1
Construction and Building Materials 1
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Table 1. Codes for this review

Code	**Description of the codes in this review**
Year	Year of publication
Author	Authors of the publication
Publication venue	The journal where the paper is published
Location	The location where the research was conducted
Goal of study	The intended aim and objectives for carrying out the study
Functional unit (FU)	The reference unit for the assessment
System boundary	The phases and unit processes
Life cycle assessment method	The method for conducting the LCA
Data sources	The data sources
Impact category	The environmental concerns to which the LCI analysis results are assigned
Major findings	Main results that are related to the goal of the study
Future needs	Limitations or future directions identified by the authors of the publication

Table 2. Classification of the retrieved publications based on their goal of study

Classification		Description of the classifications	Publication
Typical application	Road evaluation	To evaluate the environmental impacts of a road project	26
	Alternative design	To compare different designs for a given road, such as rehabilitation methods, maintenance schemes, and various lifespan designs	19
	Material evaluation	To evaluate the environmental impacts of a material, such as a mixture, an additive, or an eco-friendly material (e.g., industrial by-products, recycled materials, and other modified materials)	51
	Material comparison	To compare different materials, such as concrete versus asphalt, and different asphalt products	17
Modelling development	Framework/tool development	To develop a framework or calculation tool for road evaluation	24
	LCC + LCCA	To develop a method that integrates LCA and lifecycle cost analysis (LCCA) in road evaluation	23
	New impacts	To develop a method to capture new impacts that are rarely considered in previous studies, including traffic congestion, albedo effects, rolling resistance, carbonation, noise, and lighting	30
Others		The goal of the study is not included in the above classifications	9

Table 3. Pros and cons of existing LCA methods

Comparison	Methods	Pros	Cons	Frequency
Process-based LCA (P-LCA)	• Identifies the input and output in each process of production of a product or service[1] • Provides assessment for specific processes[1]	• Can obtain detailed results for each process[1] • Has advantages when evaluating the use and EOL stages[2] • Allows comparison of specific products[2]	• Setting a system boundary is difficult[3] • "Cut-off" errors[1,3,4] • Unable to capture circularity effects[1] • Costly and time-consuming[1,3]	67 (71.28%)
EIO-LCA	• Provides an assessment of the whole economic system[1] • Quantifies interrelationships between various sectors of the economy[1]	• The analysis boundary is the whole economy; no "cut-off" errors[1] • Solves the problem of circularity effects[1] • Less costly and faster[1] • Reflects direct and indirect interactions between different economic sectors; provides both economic and sector-wide results[1]	• Unable to reflect particular processes owing to the heterogeneousness of sectors and the use of national average data[3] • Homogeneity and linearity assumptions[4] • Aged input–output data[3,4] • High levels of sector aggregation[3,4]	6 (6.38%)
Hybrid LCA	Usually combines the two methods by using IO data to complement the upstream processes, which are often excluded in traditional P-LCA[3]	• Overcomes the problem of the costly, time-consuming, or missing data of P-LCA[3,4,5] • Reduces "cut-off" errors of P-LCA and improves the consistency across the stages of the road life cycle[3,4,5] • Improves the reliability of EIO-LCA[3,4,5]	• Lack of standard methodological framework[5] • Lack of mature tool[5]	11 (11.70%)

Note:

[1] Hendrickson et al. (2006); [2] Choi et al. (2016); [3] Suh et al. (2004); [4] Bullard et al. (1978); [5] Crawford et al. (2018).

This table include 84 papers and the remaining 10 papers are not presented because their methods are not reported and difficult to tell from the context.

Table 4. Summary of highly cited LCA studies in roads: system boundary

Studies	**System boundary**					
	Material production	Transportation	Construction	Use	M&R	EOL
Chiu et al. (2008)	√	√	×	×	√	×
Treloar et al. (2004)	√	×	√	√	√	×
Chowdhury et al. (2010)	√	×	×	×	×	×
Birgisdottir et al. (2006)	√	√	√	×	√	×
Birgisdottir et al. (2007)	√	√	√	×	√	×
Wang et al. (2012)	√	√	×	√	√	×
Huang et al. (2009)	√	√	×	×	√	×
Vidal et al. (2013)	√	√	√	√	√	√
Carpenter et al. (2007)	-	-	-	-	-	-
Cass and Mukherjee (2011)	√	×	√	×	×	×
Yu and Lu (2012)	√	×	√	√	√	√
Olsson et al. (2006)	√	√	√	√	×	×
Loijos et al. (2013)	√	×	√	√	√	√
Jullien et al. (2006)	√	-	√	×	×	×
Anastasiou et al. (2015)	√	√	√	×	√	√
Aurangzeb et al. (2014)	√	√	√	×	√	×
Oliver-Sola et al. (2009)	√	√	√	×	√	○
Roth and Eklund (2003)	-	-	-	-	-	-
Tatari et al. (2012)	√	√	√	×	×	×
Giani et al. (2015)	√	√	√	×	√	√
Santos et al. (2017)	√	√	√	√	√	√
Farina et al. (2017)	√	×	√	×	√	×

Notes:

1. √ – included; ○ – limited consideration; - – not specified; × – not included;

2. Highly cited means twenty most cited papers and two recent highly cited publications with more than 10 citations.

Table S1. Summary of highly cited LCA studies in roads: goal of study and functional parameters

Citation	Studies	Goal of study	Location	Functional unit (FU)	Roadway classification	Lane width	Shoulder width	Layers & Thickness	Lanes type and number	Analysis Period
67	Chiu et al. (2008)	Material evaluation	China (Taiwan)	Length: per lane-kilometer	-	2.65 m	-	5 cm	Asphalt, 1	40 years
58	Treloar et al. (2004)	Road evaluation	Australia	Length: 5 km	Rural roads	-	-	-	Various, -	40 years, 20 years
53	Chowdhury et al. (2010)	Material evaluation	US	Length: 1 km	-	2.5 m	-	600 mm	-, -	-
53	Birgisdottir et al. (2006)	Material evaluation	Denmark	Length: 1 km	Secondary road	3.5 m	2.1 m	0.7 m in total	Asphalt, 2	100 years
53	Birgisdottir et al. (2007)	Material evaluation	Denmark	Length: 1 km	Secondary road	7 m in total	-	0.37 m	Asphalt, -	100 years
52	Wang et al. (2012)	Alternative design	US	-	Rural road	-	-	-	Both asphalt and concrete, -	-

Citation	Studies	Goal of study	Location	Functional unit (FU)	Roadway classification	Lane width	Shoulder width	Layers & Thickness	Lanes type and number	Analysis Period
50	Huang et al. (2009)	Alternative design	UK	Length: 2.6 km	-	3.5 m	-	200 mm base; 60 mm binder course; 40/50 mm layer	Asphalt, 2	-
50	Vidal et al. (2013)	Material evaluation	Spain	Length: 1 km	1000 vehicles per day (8% heavy vehicles)	13 m	-	0.08 m asphalt layer	Asphalt, 2	40 years
45	Carpenter et al. (2007)	Material evaluation	US	Length: 305 m	Highway	10.4 m	1.5 m	Various	Asphalt, -	-
44	Cass and Mukherjee (2011)	Road evaluation	US	Length: per lane mile	Highway	24 feet	-	-	Concrete, 4	-
39	Yu and Lu (2012)	Alternative design	US	Length: one km overlay system	Highway	3.6 m	1.2 m, 2.7 m	225 mm PCC surface; 250 mm base course	Various, 2*2	40 years

Citation	Studies	Goal of study	Location	Functional unit (FU)	Roadway classification	Lane width	Shoulder width	Layers & Thickness	Lanes type and number	Analysis Period
31	Olsson et al. (2006)	Material evaluation	Sweden	Length: 1 km road	-	-	-	-	-, -	-
29	Loijos et al. (2013)	Road evaluation	US	Various	Various	Various	Various	Various	Concrete, various	40 years
29	Jullien et al. (2006)	Material evaluation	France	Area: a 3.8 m * 150 m road section	-	3.8 m	-	0.07 m	Asphalt, -	-
28	Anastasiou et al. (2015)	Material comparison	Greece	Length: 1 km	Urban road (low traffic)	7.3 m in total	-	-	Concrete, 2	40 years
28	Aurangzeb et al. (2014)	Material evaluation	US	Length: a 1.6 km lane	-	-	1.8 m	254 mm binder course; 51 mm surface course	Asphalt, 1	45 years
28	Oliver-Sola et al. (2009)	Alternative design	Spain	Area: 1 m^2 of sidewalk	Urban	-	-	All layers	Concrete, -	45 years
26	Roth and Eklund (2003)	Material evaluation	Sweden	-	-	-	-	-	-, -	-

Citation	Studies	Goal of study	Location	Functional unit (FU)	Roadway classification	Lane width	Shoulder width	Layers & Thickness	Lanes type and number	Analysis Period
25	Tatari et al. (2012)	Material comparison	US	Length: 1 km	-	7.2 m (total)	-	Different asphalt surface layer; 10 in. base course layer	Asphalt, 2	30 years
23	Giani et al. (2015)	Material evaluation	Italy	Length: 1 km	Suburban road	15 m (total)	-	25 cm	Asphalt, 2 * 2	30 years
13	Santos et al. (2017b)	Material evaluation	US	Length: 1 km	Highway	3.66 m	-	-	Asphalt, 2	50 years
11	Farina et al. (2017)	Material evaluation	-	Length: 1 m of built pavement layer	-	Depending on the project	-	Depending on the project	Asphalt, -	18 years, 20 years

Notes:

1. - – not specified;

2. Highly cited means twenty most cited papers and two recent highly cited publications with more than 10 citations.

Table S2. Summary of highly cited LCA studies in roads: LCI method, database and tool, impact categories, and sensitivity and uncertainty analysis

Studies	Method	Data sources	Tool	Output/Impact categories	Sensitivity	Uncertainty
Wang et al. (2012)	Combined models	Stripple (1998); Athena Institute (2006); EcoInvent; USLCI; Cement LCI by PCA	-	Energy use, Greenhouse gas (GHG) emissions	√	√
Birgisdottir et al. (2006)	P-LCA	Standard sources, i.e., Stripple (2001); Environmental Design of Industrial Products database	ROAD-RES model	Leaching of heavy metals and salts from the bottom ash, Resource and energy consumption, Emissions (CO_2, NO_x), Salts used for road salting	×	×
Vidal et al. (2013)	P-LCA	Field study; Ecoinvent; Published literature	SimaPro	All 18 ReCipe Midpoint impact categories; 3 ReCipe endpoint damage categories; cumulative energy demand	×	√
Giani et al. (2015)	P-LCA	Key processes: Company survey; Upstream processes: Ecoinvent database; published literature	SimaPro 7.3	All 18 ReCipe Midpoint impact categories	×	√
Oliver-Sola et al. (2009)	P-LCA	Ecoinvent 1.2 database	EcoConcrete LCA tool	Abiotic depletion potential, Acidification potential, Eutrophication potential, Global warming potential (GWP), Human toxicity potential, Ozone layer depletion potential, Photochemical ozone creation potential	×	√

Studies	Method	Data sources	Tool	Output/Impact categories	Sensitivity	Uncertainty
Chiu et al. (2008)	P-LCA	Eco-indicator 99	-	Energy sources, Resources	×	×
Chowdhury et al. (2010)	P-LCA	Published literature; CMLCA	CMLCA	Acidification potential, Aquatic ecotoxicity potential, Aquatic sediment ecotoxicity potential, Energy consumption, GWP, Human toxicity potential, Terrestrial ecotoxicity potential	×	×
Huang et al. (2009)	P-LCA	Published literature and publications	VISSIM, EnvPro	Acidification, Eco-toxicity, Eutrophication, Global warming, Human toxicity, Photo-oxidant formation	×	×
Loijos et al. (2013)	P-LCA	Published literature and LCI databases	-	GWP	√	×
Yu and Lu (2012)	P-LCA	Portland Cement Association; Swedish Environmental Research Institute	-	Energy (Primary and feedstock), GHG (CO_2, CH_4, N_2O, VOC, NO_x, CO, PM_{10}, SO_x)	√	√
Birgisdottir et al. (2007)	P-LCA	-	ROAD-RES model	Acidification, Ecotoxicity in water/soil, Global Warming, Human Toxicity via air/water/soil, Nutrient Enrichment, Photochemical Ozone Formation, Stored Ecotoxicity to water/soil, Stratospheric Ozone Depletion	√	×

Studies	Method	Data sources	Tool	Output/Impact categories	Sensitivity	Uncertainty
Olsson et al. (2006)	P-LCA	-	-	Emissions to air (SO_2, NO_x, CO, CO_2, HC, CH_4, VOC, N_2O, and particles) and water (COD, N-tot, Oil, Phenol, As, Cd, Cr, Cu, Ni, Pb, and Zn), Resources use (natural aggregates, energy)	√	×
Jullien et al. (2006)	P-LCA	-	-	Odors, PAH, VOC	×	×
Anastasiou et al. (2015)	P-LCA	-	SimaPro 7.1	GWP_{100}, Resource use	√	×
Farina et al. (2017)	P-LCA	-	SimaPro 7.3	17 ReCiPe midpoint categories; 3 ReCiPe endpoint damage categories	×	×
Cass and Mukherjee (2011)	Hybrid	Site investigation using FieldManager	SimaPro 7, EIO-LCA, e-CALC	CO_2 emissions	×	×
Tatari et al. (2012)	Hybrid	Published literature and report; National Renewable Energy Laboratory LCI database	-	CH_4, CO, CO_2, N_2O, PM, SO_2, Cumulative mass, Ecological cumulative exergy consumption, Energy, Industrial cumulative exergy consumption	√	√

Studies	Method	Data sources	Tool	Output/Impact categories	Sensitivity	Uncertainty
Treloar et al. (2004)	Hybrid	Published literature	-	Energy	×	×
Aurangzeb et al. (2014)	Hybrid	-	-	Energy consumption, GHG emissions (CH_4, CO_2, N_2O)	×	×
Santos et al. (2017b)	Hybrid	-	EIO-LCA model	Acidification air (AC), Eutrophication air (EU), Human health criteria pollutants (HH), Photochemical smog formation (PSF)	√	√
Roth and Eklund (2003)	-	-	-	-	×	×
Carpenter et al. (2007)	-	-	PaLATE, HYDRUS2D	CO, CO_2, NO_X, PM_{10}, SO_2, Energy, Hg, HTP (Cancer), HTP (Non-cancer), Pb, RCRA HazW Gen, Water	×	×

Notes:

1. - – not specified; √ – included; × – not included;

2. Highly cited means twenty most cited papers and two recent highly cited publications with more than 10 citations.

Table S3. Overview of key findings on the contributions of different life cycle phases

Studies	**Location**	**Phases**						**Analysis Period (years)**	**Results**
		Material production	Transportation	Construction	Use	M&R	EOL		
Cass and Mukherjee (2011)	US	√	×	√	×	×	×	-	**Materials, equipment, and fuel production**: 90%–94% of the CO_2 emissions; Equipment use and transportation: 6–10%
Santos et al. (2015)	Portugal	√	√	√	√	√	√	40	**Materials and usage phases**: major contribution to overall environmental impacts (low-volume traffic roads: materials phase contributes the most; high-volume traffic roads: usage phase dominates)
Loijos et al. (2013)	US	√	×	√	○	√	√	40	Year one generates the **majority of emissions** (materials production, pavement construction)
Kayo et al. (2015)	Japan	√	√	√	×	×	×	-	**Raw material procurement** - 88%; Material production - 7%; Transportation - < 1%; Construction: 4%
Kang et al. (2014)	US	√	√	√	×	×	×	-	The energy consumption and GWP in the **material phase** is remarkably higher than in the construction phase.
Mendoza et al. (2012)	Spain	√	×	√	×	×	√	> 45	**Construction materials** have the highest environmental impact (48–87%)

				Phases				Analysis	
Oliver-Sola et al. (2009)	Spain	√	√	√	×	√	○	45	Main contributor: **cement production** (especially clinker)
Weiland and Muench (2010)	US	√	√	√	×	√	×	50	**Material production** (cement, asphalt, HMA, PCC) dominates all impact categories
Yu and Lu (2012)	US	√	×	√	√	√	√	40	**Materials, congestion, and usage** contribute the most to air emissions and energy consumptions
Chen et al. (2016)	US	√	×	√	√	√	√	20, 40	**Material module, usage module**: two dominators
Choi et al. (2016)	US	√	√	√	×	√	√	50	**Cement manufacturing:** top-contributing sector
Mazumder et al. (2016)	US	√	√	√	√	√	×	50	**Material phase**: 97% of overall human toxicity in water (asphalt)
Araujo et al. (2014)	-	√	×	√	√	√	√	20	The energy consumption of the **use stage** is about 700 times higher than that of the construction phase

Notes:

1. √ – included; ○ – limited consideration; - – not specified; × – not included;

2. Highly cited means twenty most cited papers and two recent highly cited publications with more than 10 citations.

Estimation of environmental impacts of roads through life cycle assessment: a critical review and future directions

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Abstract: Motivated by the lack of a systematic analysis of the use of life cycle assessment (LCA) to estimate the environmental impacts of roads, this study conducts a critical review to examine the methods, common practices, limitations, and underlying reasons, so that future directions can be recommended. In this work, 94 papers that adopt LCA methods to assess the environmental impacts over the whole life cycle of roads were analyzed. The results demonstrate that the process-based LCA remains the most commonly adopted LCA method; however, the hybrid LCA has been gradually recognized. After examining the goal and scope definition, life cycle inventory, life cycle impact assessment, and life cycle interpretation of these studies, it was found that the current LCA applications in roads face limitations owing to the inconsistent and inappropriate selection of the functional unit, limited consideration of the maintenance and repair, use, and end-of-life phases, limited reporting of data sources, lack of standardized impact assessment procedures, and lack of sensitivity and uncertainty analyses. These limitations can be attributed to the lack of a standardized LCA procedure for roads. There is also a lack of LCA studies focusing on network-level analysis, which may restrict the use of LCA to assist policy making in road planning and management. In addition, the time effect is rarely considered to reflect the dynamic changes of environmental impacts over the project life cycle. Therefore, future directions are recommended accordingly. Improvements in these areas are expected to generate more reliable LCA results for informed decision making.

Keywords: Life cycle assessment (LCA), roads, sustainable development, green infrastructure

1 Introduction

Roads play a significant role in the transport network as people increasingly rely on vehicles for daily travel. A large network of roads causes adverse environmental impacts, such as global warming, energy consumption, landscape transformation, and soil acidification (Findlay and Bourdages, 2000; Santos et al., 2015). Construction works and regular maintenance of roads require materials that are produced through highly carbon-intensive and energy-demanding processes (Santos et al., 2015). In addition, road networks worldwide are also a major cause of significant biodiversity loss due to movement of species, habitat fragmentation, and increase of human access to existing natural habitats (Alkemade et al., 2009; Findlay and Bourdages, 2000). Green designs and practices in the road sector are highly encouraged by transportation authorities to mitigate the adverse environmental impacts (Wu et al., 2017).

The life cycle assessment (LCA) approach examines the environmental impacts of products/processes (Santero et al., 2011b). Unlike other sectors, the use of LCA in road assessment is still in its early stage. The first LCA study on roads was conducted in the 1990s (Inyim et al., 2016). Over the last two decades, LCA has attracted increasing interest as a method to evaluate the sustainability of roads. The current application of LCA in road evaluation often follows the ISO 14044 (2006) standard. However, this standard is primarily designed for the environmental assessment of manufactured products rather than infrastructure projects such as roads. As roads have their own unique characteristics, existing LCA practices may not be suitable in this area (Batouli and Mostafavi, 2017).

For example, when defining the goal and scope of an LCA analysis, it is a common practice to set a pre-defined analysis period and functional unit (FU) for a given product/process (ISO 14044, 2006). However, for road projects, to ensure the continued functioning of a road, maintenance and rehabilitation are needed at regular intervals and road decommissioning is relatively rare. It is therefore difficult to pre-define a strict system boundary for a road (Batouli and Mostafavi, 2017). Furthermore, the performance of a road changes as the road condition deteriorates. The widely used FUs, including length (e.g., lane-kilometer, lane-mile) and area (e.g., square-meter), are unable to capture such dynamic changes (Batouli and Mostafavi, 2017). More importantly, owing to the changing road performance, the maintenance strategies and their frequency and impact on the sustainability of roads are difficult to be accurately predicted and modeled. However, these problems, along with their root causes, have not been widely recognized in current studies. Recently, researchers began to realize these limitations, such as the inconsistent selection of FUs and system boundaries (Inyim et al., 2016). Therefore, a systematic review of the current development and implementation of LCAs in road projects is needed to comprehensively explore their limitations so that future studies can better address them.

~~This study aims to thoroughly investigate the current implementations and limitations of the LCA approach in road projects and identify potential improvements in this specific research area. Although~~For now, there are already a few isolated publications that have reviewed the existing LCA research on roads or road pavements. For example, Anthonissen et al. (2016), Balaguera et al. (2018), and Jamshidi et al. (2017) conducted reviews on environmental impacts of sustainable alternative construction methods or construction materials for roads. Santero et al. (2011a, 2011b) ~~Santero et al. (2011a)~~reviewed 15 pavement LCA related works, pointing out several limitations of the reviewed studies and environmental impact contributors to be considered in future studies. Inspired by Santero et al. (2011a), AzariJafari et al. (2016)

investigated recent publications since 2011 to capture the latest development on the modeling of usually missing components such as pavement surface roughness, albedo effect, carbonation, etc. In addition, Inyim et al. (2016) conducted a systematic review on 32 papers published between 1996 and 2015, with an attempt to reach a conclusion on the comparison of environmental sustainability between asphalt and concrete pavements. ~~this~~ This study is distinct from the aforementioned ones in three ways. In contrast to previous reviews, which have focused on asphalt pavements (e.g. Wang et al., 2018) or alternative materials/construction technologies (e.g. Jamshidi et al., 2013), this study includes studies that cover a variety of LCA application areas. In addition, it covers the analysis period from 2003 to 2019, with 2017 to 2019 accounting for 34% of the publications. Therefore, this review offers an update on the most recent developments and applications of LCA in roads. ~~In addition~~Moreover, this study provides a new angle of understanding the use of LCA in roads by considering the nature of LCA and the unique characteristics of roads.

By conducting a critical review, this work aims to fulfill three objectives: 1) to draw a picture of the current methods and implementation of LCA in road projects from a life cycle point of view; 2) to identify the limitations and challenges of using LCA in the environmental assessment of roads; and 3) to point out future directions. The rest of this paper is organized as follows. Section 2 provides the research method for this review and Section 3 presents an overview on existing publications. Section 4 summarizes the main findings of this study, including the three fundamental LCA approaches and their applications in road projects. Section 5 discusses the limitations of existing studies and investigates future directions of LCA in road projects, and Section 6 concludes this review.

2 Research method

A six-step approach, based on Thomé et al. (2016), was adopted so that a systematic review could be conducted. A similar review process is also used by Wan et al. (2018). The first step was to define the review scope. The aim of this review was to investigate the development and implementation of the LCA approach in road projects. Therefore, all review activities were centered on this aim.

The second step was related to the identification of relevant articles through searching techniques, including the selection of databases and keywords. The Web of Science database was selected as the primary source because of its coverage and prime quality (Li et al., 2017). The searching terms, (“life cycle assessment” OR “LCA”) AND (“road” OR “pavement”) were used to identify articles that contain such keywords in the title, abstract, or keywords sections. Only peer-reviewed journal papers and reviews were selected based on quality considerations (Li et al., 2019). Other publication types, such as conference papers, theses, and letters were excluded.

Steps three and four were related to data collection and quality evaluation. Using the searching techniques mentioned above, 597 potentially relevant articles were identified, among which 220 are directly related to road or pavement LCA. It should be noted that roads are usually classified into three types of facilities, including earthwork zones, bridges, and tunnels (Park et al., 2016). Most studies are limited to the earthwork zone of paved roads. To ensure that the research aim was consistent, 21 studies on unpaved roads, embankments, and trenches, roundabout intersections, bridges, and tunnels were excluded in this review. The screening process is also adopted by Inyim et al. (2016) and Wan et al. (2018). As a result, a total of 199 peer-reviewed journal papers were retrieved.

The last two steps were data analysis and interpretation. Content analysis was selected as the method for data analysis because it was recommended as the best fit for analyzing textual data

(Erlingsson and Brysiewicz, 2017). Table 1 presents the codes for the content analysis, including year, author, journal, location, goal of study, FU, system boundary, life cycle assessment method, data sources, impact category, major findings, and future needs. These codes were also aligned with the four-step LCA. For example, the FU and system boundary were related to the goal and scope definition.

Table 1. Codes for this review

Code	**Description of the codes in this review**
Year	Year of publication
Author	Authors of the publication
Publication venue	The journal where the paper is published
Location	The location where the research was conducted
Goal of study	The intended aim and objectives for carrying out the study
Functional unit (FU)	The reference unit for the assessment
System boundary	The phases and unit processes
Life cycle assessment method	The method for conducting the LCA
Data sources	The data sources
Impact category	The environmental concerns to which the LCI analysis results are assigned
Major findings	Main results that are related to the goal of the study
Future needs	Limitations or future directions identified by the authors of the publication

3 Overview of existing LCA studies on road projects

A preliminary analysis of the 199 selected papers published from 2003 to 2019 was conducted to provide descriptive information of these studies, including the publication years, journal distribution, and general classifications.

3.1 Publication distribution

Figure 1 illustrates the distributions of the publications. It shows that LCA on roads has attracted substantial research interest since 2012, which demonstrates the rising interest about this research area in the LCA community in recent years.

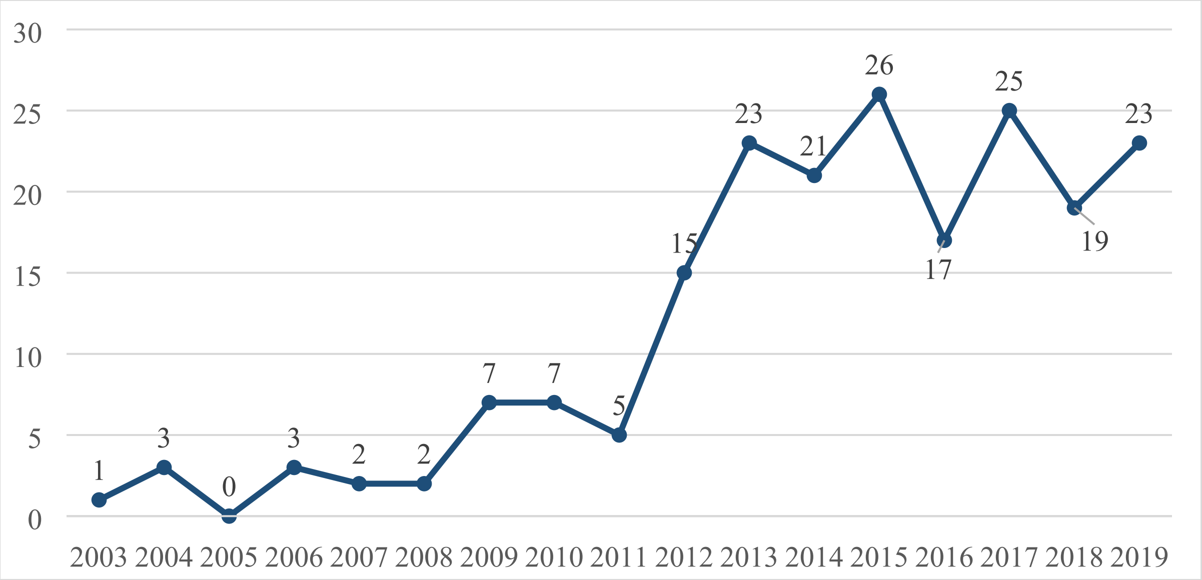

Figure 1. Distribution of retrieved publications by year

Appendix A illustrates the distribution of these articles in publication venues. In total, 50 journals have published relevant papers. Among these journals, the Journal of Cleaner Production has the highest number of publications (41), followed by Transportation Research Record: Journal of the Transportation Research Board and Transportation Research Part D: Transport and Environment, with 21 and 19 relevant articles, respectively.

3.2 General themes

In general, there were two main themes based on the goals, including the application of LCA in roads (113, 56.8%) and the modeling development of LCA in roads (77, 38.7%). Table 2 presents the description of these two main themes. In the application theme, the study goal was the application of LCA to evaluate roads or road materials, following the LCA processes defined in ISO 14044 (2006). Among these studies, 94 papers targeted the road structure, whereas the other 19 targeted the materials. In the modeling development theme, the study purpose was to develop an LCA tool for roads, or to introduce a method for calculating certain new impacts that were often excluded in previous studies (e.g., traffic delay and rolling resistance). Based on the research aim and objectives, the 94 papers focusing on the application of LCA in roads were targeted first. Table 2 and Figure 2 present the definition and distribution of themes, respectively, which show that the evaluation of materials is attracting immense research interest.

Table 2. Classification of the retrieved publications based on their goal of study

Classification		**Description of the classifications**	**Publication**
Typical application	Road evaluation	To evaluate the environmental impacts of a road project	26
	Alternative design	To compare different designs for a given road, such as rehabilitation methods, maintenance schemes, and various lifespan designs	19
	Material evaluation	To evaluate the environmental impacts of a material, such as a mixture, an additive, or an eco-friendly material (e.g., industrial by-products, recycled materials, and other modified materials)	51
	Material comparison	To compare different materials, such as concrete versus asphalt, and different asphalt products	17
Modelling development	Framework/tool development	To develop a framework or calculation tool for road evaluation	24
	LCC + LCCA	To develop a method that integrates LCA and lifecycle cost analysis (LCCA) in road evaluation	23
	New impacts	To develop a method to capture new impacts that are rarely considered in previous studies, including traffic congestion, albedo effects, rolling resistance, carbonation, noise, and lighting	30

Classification	Description of the classifications	Publication
Others	The goal of the study is not included in the above classifications	9

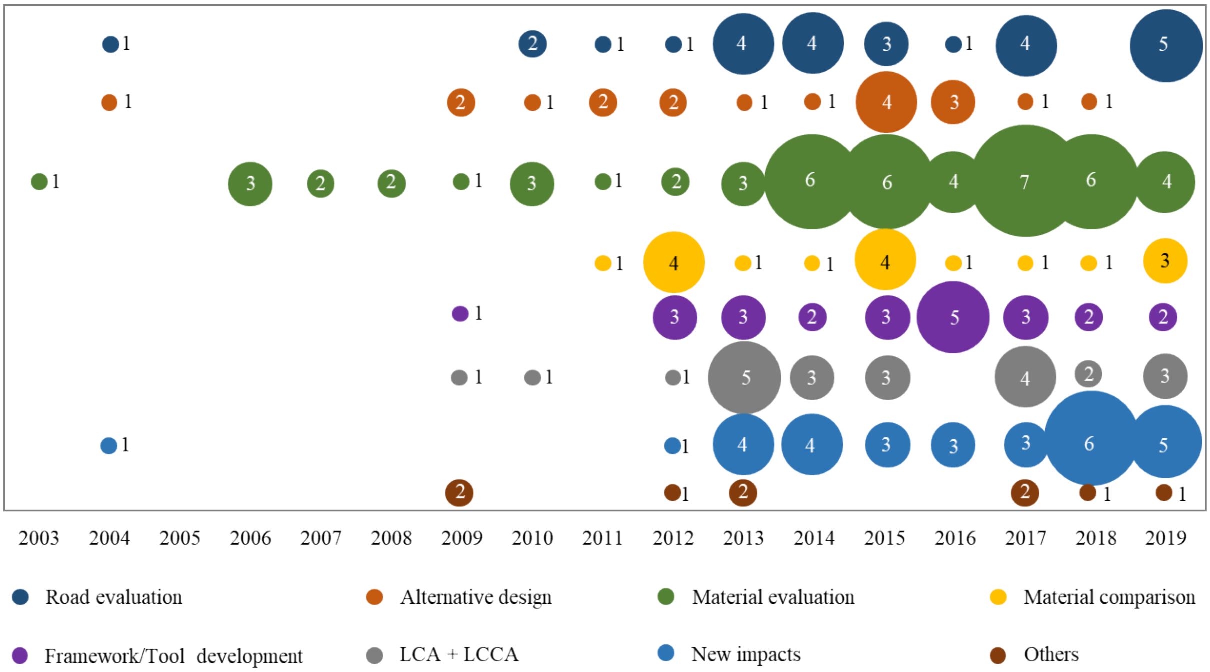

Figure 2. Distribution of publications by theme and year

4 Critical review of the approaches and applications of LCA in roads

In this section, the commonly used LCA approaches are compared and findings on the applications of LCA in roads are presented following the typical procedures of conducting an LCA study defined in ISO 14044 (2006).

4.1 LCA approaches

LCA is often categorized into process-based LCA (P-LCA), environmental input–output LCA (EIO-LCA), and hybrid LCA (Santos et al., 2017). P-LCA defines the system boundary by processes and divides the target system into a series of process flows to model the inputs and outputs of every process (Horvath and Hendrickson, 1998). It has been widely adopted in environmental evaluation of roads (e.g. Chiu et al., 2008; Chowdhury et al., 2010; Huang et al., 2009), with 67 (71.3%) studies using this method. However, this method requires data on consumption and environmental output to be obtained for every process, which is labor- and time-intensive. Therefore, P-LCA is often expensive and time-consuming, especially for a complex system that encompasses thousands of processes (Suh et al., 2004). It also has the risk of excluding a large number of inputs for upstream processes, which may have a significant effect on the total inventory (Choi et al., 2016).

To simplify the LCA and generate more comprehensive LCA results, EIO-LCA is proposed. In EIO-LCA, the boundary often spans the global economy, which includes the entire chain of suppliers (Suh et al., 2004). When producing the products in a sector, inputs, which are the outputs of other sectors, are required. Because each sector has environmental impacts per dollar of output, the overall environmental impacts can be quantified by summing up the products of the inputs and the environmental impacts of the corresponding sectors (Horvath and Hendrickson, 1998). Although EIO-LCA is able to improve the completeness of the traditional method, it faces problems such as the age of input–output data, homogeneity assumption, use of national average data, and high levels of sector aggregation (Choi et al., 2016; Hendrickson et al., 2006). As can be observed in Table 3, EIO-LCA has not been fully embraced, with only 6 studies conducted in the evaluation of roads (6.4%).

Hybrid LCA, which combines the two methods by using input–output (IO) data to complement the processes that are excluded in P-LCA, was later proposed (Bullard et al., 1978; Suh et al., 2004). The main advantage of this approach is that it improves the completeness of P-LCA while raising the reliability of EIO-LCA (Bullard et al., 1978). Table 3 summarizes the advantages and disadvantages of each method.

Table 3. Pros and cons of existing LCA methods

Comparison	Methods	Pros	Cons	Frequency
Process-based LCA (P-LCA)	• Identifies the input and output in each process of production of a product or service[1] • Provides assessment for specific processes[1]	• Can obtain detailed results for each process[1] • Has advantages when evaluating the use and EOL stages[2] • Allows comparison of specific products[2]	• Setting a system boundary is difficult[3] • "Cut-off" errors[1,3,4] • Unable to capture circularity effects[1] • Costly and time-consuming[1,3]	67 (71.3%)
EIO-LCA	• Provides an assessment of the whole economic system[1] • Quantifies interrelationships between various sectors of the economy[1]	• The analysis boundary is the whole economy; no "cut-off" errors[1] • Solves the problem of circularity effects[1] • Less costly and faster[1] • Reflects direct and indirect interactions between different economic sectors; provides both economic and sector-wide results[1]	• Unable to reflect particular processes owing to the heterogeneousness of sectors and the use of national average data[3] • Homogeneity and linearity assumptions[4] • Aged input–output data[3,4] • High levels of sector aggregation[3,4]	6 (6.4%)

Comparison	Methods	Pros	Cons	Frequency
Hybrid LCA	Usually combines the two methods by using IO data to complement the upstream processes, which are often excluded in traditional P-LCA[3]	• Overcomes the problem of the costly, time-consuming, or missing data of P-LCA[3,4,5] • Reduces "cut-off" errors of P-LCA and improves the consistency across the stages of the road life cycle[3,4,5] • Improves the reliability of EIO-LCA[3,4,5]	• Lack of standard methodological framework[5] • Lack of mature tool[5]	11 (11.7%)

Note:

[1] Hendrickson et al. (2006); [2] Choi et al. (2016); [3] Suh et al. (2004); [4] Bullard et al. (1978); [5] Crawford et al. (2018).

This table include 84 papers and the remaining 10 papers are not presented because their methods are not reported.

4.2 Current applications of LCA in roads

Complying with the ISO 14044 standard (ISO 14044, 2006), a typical LCA study often follows four steps: 1) defining goal and scope, clarifying system boundaries, and determining FUs; 2) compiling the life cycle inventory (LCI) by allocating the inputs (resources) and outputs (e.g., emissions) through the life cycle; 3) assessing the potential life cycle environmental impact of the target system (which is referred to as LCIA); and 4) interpreting the results from the LCIA for conclusions and recommendations. Each step will be investigated to examine the current common practices and identify limitations in existing studies so that future directions can be proposed accordingly for further improvement.

4.2.1 Goal and scope definition

4.2.1.1 The goal of the studies

The goal of LCA plays a vital role in defining the FU, setting the system boundary, and selecting data sources (Loijos et al., 2013). Existing LCA studies on roads are usually limited to four types of goals, namely, evaluating the environmental impact of roads, alternative designs, pavement materials, and alternative materials. In addition, the majority of the studies (89, 94.7%) were conducted based on a project-level analysis. Only a few have investigated the impacts of roads in a network context to inform policymaking at the network level. Therefore, the implications of these studies are limited to project level and can hardly benefit road planners or policy makers to achieve an optimal solution at a network or national level.

4.2.1.2 Functional unit (FU)

Like applying LCA in other sectors such as the buildings sector, various FUs were used in LCA studies on roads, making it difficult to compare results across studies (Anand and Amor, 2017; Säynäjoki et al., 2017). 68 studies (72.3%) used the road length, such as kilometer, lane-kilometer, and lane-mile. In addition, 11 papers (11.7%) used the treatment area, expressed for instance in square meters, as the FU where the scope of the study involved the surface or wearing course of the pavement. Another FU is the whole road project, which was usually used when evaluating the environmental impact of a specific strategy (e.g., road closure scheme during rehabilitation and emission control strategy) on a given road project. For example, Hanson and Noland (2015) compared the vehicle emissions when adopting various staging approaches for a rehabilitation project. Other studies have also used the volume (e.g., in cubic meters, cubic yards) to evaluate the impacts of earthworks or recycling of materials (e.g. Capony et al., 2013).

The use of these FUs has limitations. A lane mile or a square meter cannot be used as a standard FU (Cass and Mukherjee, 2011). It was pointed out by AzariJafari et al. (2016) that the information related to the road specifications should include region, lane width, shoulder width, thickness, roadway type, pavement type, and analysis period. It was argued that road functions could not be appropriately reflected if the FU did not include the roadway classification, lane width, and number of lanes into account. Appendix B presents the goals of the studies, together with the FUs of the twenty most cited papers and two recent highly cited publications with more than 10 citations (referred to as the 22 HCPs). It is found that a systematic presentation of such information was rarely adopted in existing studies.

In addition, it is reported that the missing consideration of the condition of pavement is also a shortfall in existing studies (Inyim et al., 2016). Unlike other products or services, the condition of a pavement often deteriorates over the long service life and it directly influences the function of a road. For example, the pavement roughness is an important indicator for the serviceability of a road (Al-Omari, 1994) and can cause up to 70% variation in the fuel consumption impacts caused by on-road vehicles (Batouli and Mostafavi, 2017). Therefore, an FU that integrates the changeable condition and performance of the pavement is required (Batouli and Mostafavi, 2017; Inyim et al., 2016).

4.2.1.3 System boundary

There are six phases during a road's life cycle, namely, materials extraction and production, materials transportation, construction, use, M&R, and EOL phases. The materials extraction and production stage usually includes the processes for manufacturing the road materials, from the acquisition of raw materials to final material production (i.e., mixing plant operations). The construction phase considers all preservation and construction activities, including the combustion of fuels of the paving equipment. It should be noted that materials transportation from manufacturing plants to construction sites may be integrated into the construction phase (e.g. Zhang et al., 2010) or treated as a separate phase (e.g. Kayo et al., 2015), depending on the specific aims of the studies. The M&R stage deals with three types of maintenance treatment, such as routine maintenance, preservation, and rehabilitation. In addition, EOL treatments include the demolition, debris transport, recycling, and final disposal at the end of a road's service life (Celauro et al., 2015). However, there is no common agreement on what to be included in the use phase. For example, Loijos et al. (2013) only considered the effects of albedo, carbonation, roughness, and lighting, and excluded the vehicle emissions. On the contrary, Treloar et al. (2004) not only included the vehicle emissions, but considered the manufacture, use, and maintenance of vehicles as well.

The materials extraction, transportation, and construction stages were the commonly included life cycle stages, with 91 (96.8%), 59 (62.8%), and 81 (86.2%), respectively. Meanwhile, the consideration of use, M&R, and EOL stages was less frequent, with 28 (29.8%), 55 (58.5%), and 32 (34.0%) studies. Table 4 presents the summary of work in the 22 HCPs. The EOL stage is usually excluded as the total demolition and disposal of an infrastructure is not common practice or is not allowed by the national maintenance policies (e.g., Italy) (Celauro et al., 2015). More importantly, the exclusion of the use stage from most of the existing studies is seen as a significant shortfall owing to its great global warming potential in roughness, structure, and albedo (Santero et al., 2011b). The omission is attributed to the limitations of the impact assessment method for the use phase and the common assumption that different roads generate the same impacts in this stage (Inyim et al., 2016).

Table 4. Summary of highly cited LCA studies in roads: system boundary

Studies	**System boundary**					
	Material production	Transportation	Construction	Use	M&R	EOL
Chiu et al. (2008)	√	√	×	×	√	×
Treloar et al. (2004)	√	×	√	√	√	×
Chowdhury et al. (2010)	√	×	×	×	×	×
Birgisdottir et al. (2006)	√	√	√	×	√	×
Birgisdottir et al. (2007)	√	√	√	×	√	×
Wang et al. (2012)	√	√	×	√	√	×
Huang et al. (2009)	√	√	×	×	√	×
Vidal et al. (2013)	√	√	√	√	√	√
Carpenter et al. (2007)	-	-	-	-	-	-
Cass and Mukherjee (2011)	√	×	√	×	×	×
Yu and Lu (2012)	√	×	√	√	√	√
Olsson et al. (2006)	√	√	√	√	×	×
Loijos et al. (2013)	√	×	√	√	√	√
Jullien et al. (2006)	√	-	√	×	×	×
Anastasiou et al. (2015)	√	√	√	×	√	√
Aurangzeb et al. (2014)	√	√	√	×	√	×
Oliver-Sola et al. (2009)	√	√	√	×	√	○
Roth and Eklund (2003)	-	-	-	-	-	-

Studies	**System boundary**					
	Material production	Transportation	Construction	Use	M&R	EOL
Tatari et al. (2012)	√	√	√	×	×	×
Giani et al. (2015)	√	√	√	×	√	√
Santos et al. (2017)	√	√	√	√	√	√
Farina et al. (2017)	√	×	√	×	√	×

Notes:

1. √ – included; ○ – limited consideration; - – not specified; × – not included;

2. Highly cited means twenty most cited papers and two recent highly cited publications with more than 10 citations.

4.2.2 Life cycle inventory (LCI)

4.2.2.1 LCI data sources

The choice of data sources can be a major decision in LCA studies (Martínez-Rocamora et al., 2016). The International EPD® System categorizes the data into three types for the LCI phase, i.e., primary, secondary, and tertiary data. Primary data refers to first-hand data usually obtained by on-site surveys and field investigations. Secondary data can be obtained in the literature, including published articles, annual environmental reports, and commercial databases. Tertiary data, or other generic data, is often available through statistical averages (Moretti et al., 2017).

Typically, an LCA study requires project (input) and emissions data. To obtain input data, primary data such as field investigation and interview with the contractors or equipment manufacturer are preferred (e.g. Cass and Mukherjee, 2011). However, first-hand data for material production and construction activities are not always complete (Gulotta et al., 2019). Therefore, secondary data are also a common source. For emissions data, primary data is extremely difficult to obtain and only Kang et al. (2014) and Al-Qadi et al. (2015) used self-developed local or regional database. For others, Ecoinvent, U.S. LCI databases, Athena database, and published literature are important sources for secondary data. The use of different sources can lead to distinct results even for the same product, compromising the comparability across studies. In addition, not all materials are included in the databases, especially recycled materials, which may lead to inaccuracy of the assessment results (dos Santos et al., 2017). Similar findings are also reported in the building LCA (Säynäjoki et al., 2017). More importantly, there were a significant number of studies (30, 31.9%) that did not report the data source, resulting in high uncertainty in the LCI results. Appendix C lists the data sources of the 22 HCPs.

4.2.2.2 LCA Tools

The selection of LCA tools is usually related to the adopted LCI method. Most of the papers that adopted the P-LCA method used SimaPro or GaBi software (e.g. Farina et al., 2017; Giani et al., 2015; Vidal et al., 2013). For EIO-LCA, the most commonly adopted tools are the Pavement Life-cycle Assessment Tool for Environmental and Economic Effects (PaLATE), which is a spreadsheet LCA and the LCCA program designed to assess the environmental and economic impacts of pavement and roads, and the Economic Input–Output Life Cycle Assessment (EIO-LCA) model, an online tool designed to make EIO-LCA method fast, easy to use, and free. For the hybrid LCA, however, there was no widely adopted tool, which may be one of the reasons that the hybrid approach is not widely used (Crawford et al., 2018). Unlike the building sector where the uncertainties aroused from the LCA tools have been widely discussed and highlighted (e.g. Emami et al., 2019), only dos Santos et al. (2017) conducted a comparative study on LCA tools for roads. It is concluded that results can vary significantly even when the same stages are considered with the same materials and equipment use. In addition, there are also 37 (39.4%) studies of which the tools are not reported. The analyst are recommend to be cautious in selecting LCA tool and improve their awareness to report the selection (dos Santos et al., 2017). Appendix C summarizes the LCA methods and tools in the 22 HCPs.

4.2.3 Life cycle impact assessment (LCIA)

4.2.3.1 LCIA methods

LCIA connects the LCI results to its environmental impacts by assigning the results to selected impact categories (ISO 14044, 2006). According to Van den Heede and De Belie (2012), there are two main schools of impact analysis methods. The first school is a damage-oriented method represented by Eco-indicator 99, which focuses on the endpoint environmental damages (where the actual environmental effects or damages occur), such as damage to ecosystem quality, damage to human health, and damage to mineral and fossil resources. The second one is considered to be a problem-oriented or midpoint method, and a representative example is CML 2001, for quantitative modeling within the early stages of the cause–effect chain. For example, a road's climate change effect can be calculated by an endpoint method to produce environmental damage to human health, or by a midpoint method (i.e. kilograms of CO2e). To offer users the choice of the level of results, methods that combine the midpoint and endpoint, such as ReCiPe, which is a fusion of CML 2001 and Eco-indicator 99, were also available.

In the existing literature, only 18 (19.1%) papers have reported the method of impact assessment. In these studies, many (17) adopted a midpoint method, including CML 2001 midpoint method (4 papers), ReCiPe midpoint method (8 papers), TRACI midpoint method (2 papers), and 3 other midpoint methods. The popularity of the ReCiPe may be attributed to the fact that it incorporated the widely used SimaPro software (Vidal et al., 2013), and it is convenient for having combined both assessment methods. Other publications, which did not report the method of impact assessment, commonly adopted midpoint methods for selecting midpoint impact categories, such as global warming potential, acidification, and eutrophication, to name a few. Similar preference for the midpoint approach is also reported in other sectors (e.g. Yi et al., 2014). Main reasons are that the endpoint approach requires a high level of expertise and is exposed to much higher uncertainty than the midpoint approach. Nevertheless, the midpoint approach may not provide the results that decision makers really expect (Bare et al., 2000). Therefore, Bare et al. (2000) suggested that a consistent framework is needed to present both sets of results, either in a combined or parallel approach.

4.2.3.2 LCIA

Selecting impact categories and conducting the impact assessment are mandatory elements of an LCA study (ISO 14044, 2006). However, it should be noted that there is a lack of a standardized way of reporting the results.

Many studies offer simple quantification of the outputs without impact assessment. For instance, Cass and Mukherjee (2011) calculated the greenhouse gas (GHG) emissions for highway construction without conducting a further impact assessment. Such omission of the impact assessment step can introduce difficulty in the decision-making process because the simple estimation of gas emissions cannot provide intuitive information (Inyim et al., 2016). A similar limitation can also be found in comparison studies, such as in Yu and Lu (2012). However, an LCI study alone is not supposed to be used for comparative assertions (ISO 14044, 2006).

Other studies, as can be observed in Appendix C, attempted to interpret the results using impact assessment, but they selected extremely varied impact categories, making it difficult to conduct a cross comparison between different studies. Among these studies, GHG emissions and energy consumption were the most consistently used assessment metrics. Other widely used categories also included damage to the ecosystem and human health. Little consideration has been given to natural resources such as land use.

It is also found that few authors explained the reasons for choosing certain impact categories, thus not clarifying whether the selection was consistent with the goal and scope of the study. For example, Santos et al. (2015) adopted eight impact categories, whereas Santos et al. (2017) only considered four categories without providing reasons for including or excluding certain impacts. Out of these studies, only two studies, i.e., Fitch et al. (2013) and Veran-Leigh et al. (2019), elaborated the reasons for selecting each impact category.

4.2.4 Life cycle interpretation

Life cycle interpretation comprises three components, that is, identifying significant issues, checking completeness, consistency, and sensitivity, and drawing conclusions and recommendations (ISO 14044, 2006).

4.2.4.1 Phase/Process

Each stage in the life cycle of a road contributes differently to its environmental impacts. As can be observed from Appendix D, the material extraction and production stage was identified as the main contributor to the total carbon emissions and energy consumption by most studies. In this stage, the cement production process has been highlighted as the main contributor (e.g. Choi et al., 2016; Loijos et al., 2013; Oliver-Sola et al., 2009; Weiland and Muench, 2010). Current studies also pointed out the importance of the use phase (e.g. Chen et al., 2016). According to Araujo et al. (2014), the impact of the use phase on the environment was approximately 700 times higher than that of the construction phase. The use phase also dominates the environmental performance for roads with high traffic volumes (Santos et al., 2015).

4.2.4.2 Asphalt vs concrete pavement

The comparison of pavement materials such as asphalt and concrete has attracted much research attention over these years, although no general conclusion has been drawn. For example, Weiland and Muench (2010) and Yu and Lu (2012) both investigated rehabilitation alternatives. The former argued that the hot mixed asphalt pavement (HMA) had a higher energy use and the Portland cement concrete (PCC) had a higher global warming potential (GWP); the latter drew the conclusion that PCC was better than HMA in both energy use and GWP performance. A possible reason for the different results could be the overlook of impacts from the use phase and EOL phase by Weiland and Muench (2010), whereas Yu and Lu (2012) considered the whole life cycle, except for the transportation of materials. More widely agreed results may be that the asphalt pavement could offer a reduction in GWP but concrete has an advantage in pavement energy demand (e.g. Dumitrescu et al., 2014; Gschosser and Wallbaum, 2013; Gschosser et al., 2012; Weiland and Muench, 2010). It should also be noted that most studies had no or had limited consideration of the use phase, except Yu and Lu (2012), which might influence the results.

4.2.4.3 Impact of eco-friendly technologies

The reclaimed asphalt pavement (RAP) and warm mix asphalt (WMA) were the commonly investigated eco-friendly technologies in current studies. RAP allowed a reduction of the use of virgin materials and WMA was used to lower the production temperature of the asphalt mixture (Giani et al., 2015). Using RAP could have a significant potential of reducing eco burdens of both rehabilitation (Chiu et al., 2008; Turk et al., 2016) and initial construction projects (Aurangzeb and Al-Qadi, 2014; Aurangzeb et al., 2014), especially when combined with HMA (Giani et al., 2015; Vidal et al., 2013). However, the studies provided contrasting results related to the impacts of using a high content of RAP. Aurangzeb and Al-Qadi (2014) and Aurangzeb et al. (2014) proved that reductions of energy and GHG could increase with an increase of RAP content to 30%, 40%, and 50%. On the contrary, Saeedzadeh et al. (2018) reached the opposite conclusion that high RAP content could lead to higher environmental burdens. As for WMA, Liu et al. (2014) and Mazumder et al. (2016) indicated that WMA was more beneficial to the environment than HMA. On the contrary, Tatari et al. (2012), Vidal et al. (2013), and Anthonissen et al. (2015) argued that this was not necessarily true because of the significant influence of additives, especially the synthetic zeolites.

4.2.4.4 Sensitivity and uncertainty analysis

A sensitivity analysis is a compulsory element in the life cycle interpretation phase by estimating the effects of a chosen method or data on the LCA results. The aim is to evaluate the reliability of the final results by quantifying the extent to which the results are affected by uncertainties coming from data, allocation methods, or LCIA calculation. The uncertainty analysis is often used as a supplement and is supposed to quantify uncertainties, such as model inaccuracy, input uncertainty, and data variability (ISO 14044, 2006). However, limited studies have reported such results, indicating high uncertainties in the results. In total, 32 studies (34.0%) conducted a sensitivity analysis, usually on the effects of transport management and traffic growth (e.g. Mendoza et al., 2012; Yu and Lu, 2012). In addition, only 17 studies (18.1%) conducted an uncertainty analysis. In these studies, only a few complied with the requirement of ISO 14044 (2006) that sensitivity analysis is mandatory and uncertainty analysis should supplement the results. For example, Wang et al. (2012) implemented a sensitivity analysis without clearly reporting the results. Giani et al. (2015) implemented a separate uncertainty analysis without conducting a sensitivity analysis. This may suggest a need for a clearer definition and guidance of the sensitivity and uncertainty analyses based on the ISO 14044 (2006) standard.

5 Discussion and recommendations

Based on the findings and the future needs identified in existing studies, this section discusses the main limitations in LCA applications in roads and make recommendations for future directions accordingly.

ISO 14044 (2006) provides a general framework and guideline for LCA, but the challenges of selecting FUs, defining system boundaries, and mining data for a specific field are left to the researchers based on their own discretion (Loijos et al., 2013). As can be observed from the findings of this review, several limitations can be found the LCA in existing studies.

- **Goal and scope definition**

  Mostly project-oriented research. Over 90% of the existing papers are project oriented and very few investigate the impacts of roads in a network context, limiting the value for policy makers, such as road authorities (Zhang et al., 2013). The cumulative emissions of the road network of a region/nation remain unclear and it is difficult to capture the regional disparities of the emissions under the existing LCA framework (Chen et al., 2017). Therefore, region-specific strategies for reducing the emissions are difficult to be developed. Another limitation of the project-level LCA is that road maintenance works are often planned in isolation to achieve an optimal solution for the project (Galatioto et al., 2015). The decision level at the network level, as Santos et al. (2017a) and Santos et al. (2018) have suggested, is much more complicated with budget consideration. It is therefore recommended that future research needs to consider the road network as a whole so that useful implications can be drawn for policymaking.

  Inconsistent selection and definition of FU. There are various FUs being used by existing studies which makes it difficult to make comparison between studies. To improve the comparability across studies, the consistency of the use of FUs needs to be increased (Inyim et al., 2016). In addition, currently used FUs are considered insufficient to reflect the changing functions of a road. It is therefore recommended that the definition of FU should consider the evolving road performance so that the real time function of roads can be reflected (Batouli and Mostafavi, 2017).

Lack of consideration of post construction stages. The use and M & R phases can have significant environmental impacts (Santero and Horvath, 2009; Wu et al., 2014). However, only a few studies have included these phases. There is still a lack of a method to accurately decide the maintenance measures for the whole life cycle of a road due to the constantly changing circumstances. In addition, the impact sources of the use phase are not consistently defined and methods for this phase is insufficiently developed. Future studies are recommended to fully capture these phases so that reliable outcomes can be delivered (Inyim et al., 2016). Furthermore, unlike common products, roads can receive rehabilitation over and over again and therefore may not have a clear life cycle. This suggests a need to further discuss the life cycle of a road and whether or how the EOL stage should be included in a typical LCA study (Batouli and Mostafavi, 2017).

- **LCI:**

Limited report of data sources and LCA tools. Different databases and LCA tools are being used in existing studies, which can lead to distinct results even for the same product or processes (dos Santos et al., 2017). However, most authors are not aware of the uncertainty and do not report the data sources and LCA tools. Future studies are recommended to consider such uncertainty in sensitivity and uncertainty analysis (Emami et al., 2019). There is also a need for studies that compare the results generated from different data sources or LCA tools to reveal uncertainties introduced from data and tools can be revealed.

- **LCIA:**

Lack of standardized LCIA procedure. Missing impact assessment phase, limited report of LCIA method and an inconsistent selection of impact categories are identified for the LCIA step, which result in difficulties in conducting comparisons across existing work (Inyim et al., 2016). A standardized LCIA procedure is therefore needed to improve the awareness of the LCIA step and guide the selection of LCIA method and impact categories.

- **Life cycle interpretation:**

  Lack of sensitivity and uncertainty analysis. A large amount of uncertainty exists for an LCA study, including parameter (input) and data uncertainty in the LCI step and method uncertainty in the LCIA step (Bare et al., 2000). The low awareness and lack of sensitivity and uncertainty considerations indicate high uncertainties on results delivered by existing publications. Future studies should conduct such analyses in order to ensure the reliability of their results.

As can be seen from the discussion, a lack of consistency and standardization is identified in each step, which echoes the key findings of AzariJafari et al. (2016), Inyim et al. (2016), and Santero et al. (2011b). Those limitations are considered to be rooted in the incompatibility of conventional LCA method and the characteristics of roads, meaning that the ISO 14044 is not perfectly suitable for guiding the LCA applications in roads (Batouli and Mostafavi, 2017; Cass and Mukherjee, 2011). There is therefore a need to standardize the LCA approach specifically for roads in future research.

In addition, from the review, it is found that the time effect has not been well captured in existing LCA studies on roads. For example, in current practice, it is common to simply aggregate the emissions generated at different times within the life cycle without discounting the values as the LCCA studies usually do (e.g. Cass and Mukherjee, 2011; Chiu et al., 2008;

Hanson and Noland, 2015; Yu and Lu, 2012; Yu et al., 2018). The aggregated LCI results are usually interpreted to potential environmental impacts through LCIA and adopted directly for decision making, which can cause several problems. First, it is difficult to compare two road designs with different service life. Second, the global warming impact of a GHG decreases with time and the GWP value, which evaluates such impact, is very sensitive to the time horizon (Levasseur et al., 2010), and cannot be reflected by an aggregated value. More importantly, the aggregated value masks the temporal distribution of emissions along the life cycle (Yu et al., 2018). As a result, one project with low emissions at the construction phase and high emissions at the use phase may have the same LCI results as another that has a completely different emission distribution. Such practice creates difficulties in determining which project is more sustainable if the dynamic changes of the environmental impacts of emissions are not considered. Among the studies, only one study, i.e., Yu et al. (2018), has considered this effect. Therefore, taking into account the time effect should be an imperative improvement area for future studies.

6 Conclusion

LCA has been widely adopted to evaluate the environmental impacts of roads so that sustainable practices in the life cycle stages of the road, including materials extraction, transportation, construction, operation, maintenance, and EOL treatments, can be adopted. Over the past two decades, a large number of LCA studies have been conducted in road projects and a complete review of these studies is conducted. It is found that there are two general themes in the existing studies, which are the application of LCA in roads and the modeling development of LCA. Among all the application themes, P-LCA is the most commonly adopted approach. In addition, most of the current applications have a project-oriented goal of study. They are also found to be inconsistent in terms of selection of FU, lack of consideration of the

M&R, use, and EOL phases, high uncertainty due to limited report on data sources, sensitivity and uncertainty analyses, and lacking a standardized way of conducting impact assessment.

The consequences of these inconsistencies are also investigated. First, project-level studies have limited implications for policymaking. Second, the non-standardized procedure of conducting LCAs in roads is hindering their further development and implementation. Third, existing studies fail to consider the time effect of the environmental impact evaluation, causing difficulties in decision making between alternative road designs, which usually have a long life span. Therefore, it is recommended that future studies pay more attention to the network-level analysis and further standardize and tailor the LCA methods to align them with the characteristics of roads. Taking the dynamic changes in the environmental impacts of emissions into consideration in road LCA has also been highlighted for future work. Improvements in these areas can fill the existing knowledge gap and generate more reliable results to better inform both policymaking and decision making in the area of advancing the sustainability of roads.

7 Acknowledgments

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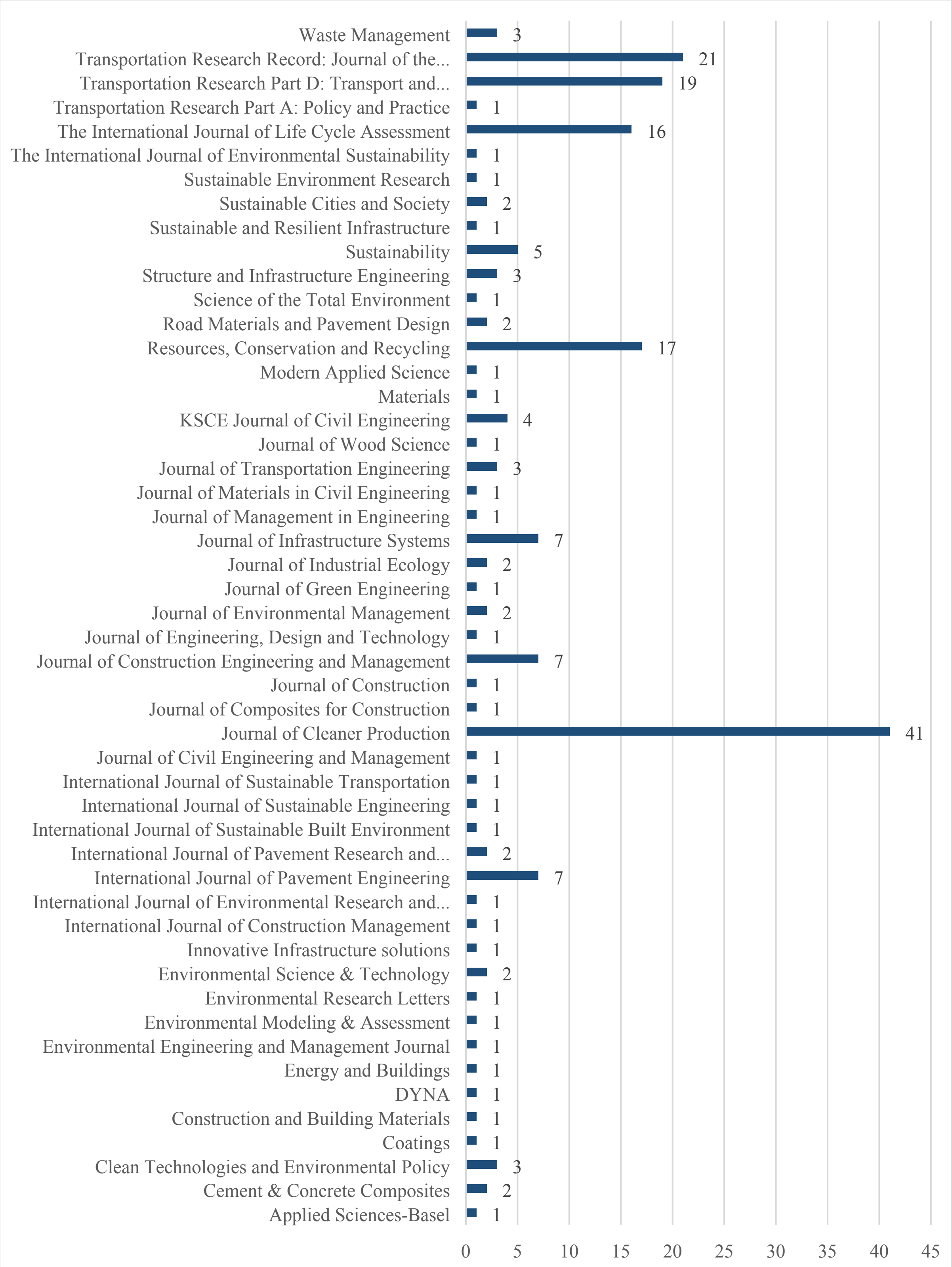
Appendix A. Distribution of retrieved publications by journal



Appendix B. Summary of highly cited LCA studies in roads: goal of study and functional parameters

Citation	Studies	Goal of study	Location	Functional unit (FU)	Roadway classification	Lane width	Shoulder width	Layers & Thickness	Lanes type and number	Analysis Period
67	Chiu et al. (2008)	Material evaluation	China (Taiwan)	Length: per lane-kilometer	-	2.65 m	-	5 cm	Asphalt, 1	40 years
58	Treloar et al. (2004)	Road evaluation	Australia	Length: 5 km	Rural roads	-	-	-	Various, -	40 years, 20 years
53	Chowdhury et al. (2010)	Material evaluation	US	Length: 1 km	-	2.5 m	-	600 mm	-, -	-
53	Birgisdottir et al. (2006)	Material evaluation	Denmark	Length: 1 km	Secondary road	3.5 m	2.1 m	0.7 m in total	Asphalt, 2	100 years
53	Birgisdottir et al. (2007)	Material evaluation	Denmark	Length: 1 km	Secondary road	7 m in total	-	0.37 m	Asphalt, -	100 years
52	Wang et al. (2012)	Alternative design	US	-	Rural road	-	-	-	Both asphalt and concrete, -	-

Citation	Studies	Goal of study	Location	Functional unit (FU)	Roadway classification	Lane width	Shoulder width	Layers & Thickness	Lanes type and number	Analysis Period
50	Huang et al. (2009)	Alternative design	UK	Length: 2.6 km	-	3.5 m	-	200 mm base; 60 mm binder course; 40/50 mm layer	Asphalt, 2	-
50	Vidal et al. (2013)	Material evaluation	Spain	Length: 1 km	1000 vehicles per day (8% heavy vehicles)	13 m	-	0.08 m asphalt layer	Asphalt, 2	40 years
45	Carpenter et al. (2007)	Material evaluation	US	Length: 305 m	Highway	10.4 m	1.5 m	Various	Asphalt, -	-
44	Cass and Mukherjee (2011)	Road evaluation	US	Length: per lane mile	Highway	24 feet	-	-	Concrete, 4	-
39	Yu and Lu (2012)	Alternative design	US	Length: one km overlay system	Highway	3.6 m	1.2 m, 2.7 m	225 mm PCC surface; 250 mm base course	Various, 2*2	40 years

Citation	Studies	Goal of study	Location	Functional unit (FU)	Roadway classification	Lane width	Shoulder width	Layers & Thickness	Lanes type and number	Analysis Period
31	Olsson et al. (2006)	Material evaluation	Sweden	Length: 1 km road	-	-	-	-	-, -	-
29	Loijos et al. (2013)	Road evaluation	US	Various	Various	Various	Various	Various	Concrete, various	40 years
29	Jullien et al. (2006)	Material evaluation	France	Area: a 3.8 m * 150 m road section	-	3.8 m	-	0.07 m	Asphalt, -	-
28	Anastasiou et al. (2015)	Material comparison	Greece	Length: 1 km	Urban road (low traffic)	7.3 m in total	-	-	Concrete, 2	40 years
28	Aurangzeb et al. (2014)	Material evaluation	US	Length: a 1.6 km lane	-	-	1.8 m	254 mm binder course; 51 mm surface course	Asphalt, 1	45 years
28	Oliver-Sola et al. (2009)	Alternative design	Spain	Area: 1 m^2 of sidewalk	Urban	-	-	All layers	Concrete, -	45 years
26	Roth and Eklund (2003)	Material evaluation	Sweden	-	-	-	-	-	-, -	-

Citation	Studies	Goal of study	Location	Functional unit (FU)	Roadway classification	Lane width	Shoulder width	Layers & Thickness	Lanes type and number	Analysis Period
25	Tatari et al. (2012)	Material comparison	US	Length: 1 km	-	7.2 m (total)	-	Different asphalt surface layer; 10 in. base course layer	Asphalt, 2	30 years
23	Giani et al. (2015)	Material evaluation	Italy	Length: 1 km	Suburban road	15 m (total)	-	25 cm	Asphalt, 2 * 2	30 years
13	Santos et al. (2017)	Material evaluation	US	Length: 1 km	Highway	3.66 m	-	-	Asphalt, 2	50 years
11	Farina et al. (2017)	Material evaluation	-	Length: 1 m of built pavement layer	-	Depending on the project	-	Depending on the project	Asphalt, -	18 years, 20 years

Notes:

1. - – not specified;

2. Highly cited means twenty most cited papers and two recent highly cited publications with more than 10 citations.

Appendix C. Highly cited LCA studies in roads: LCI method, database and tool, impact categories, and sensitivity and uncertainty analysis

Studies	Method	Data sources	Tool	Output/Impact categories	Sensitivity	Uncertainty
Wang et al. (2012)	Combined models	Stripple (1998); Athena Institute (2006); EcoInvent; USLCI; Cement LCI by PCA	-	Energy use, Greenhouse gas (GHG) emissions	√	√
Birgisdottir et al. (2006)	P-LCA	Standard sources, i.e., Stripple (2001); Environmental Design of Industrial Products database	ROAD-RES model	Leaching of heavy metals and salts from the bottom ash, Resource and energy consumption, Emissions (CO_2, NO_x), Salts used for road salting	×	×
Vidal et al. (2013)	P-LCA	Field study; Ecoinvent; Published literature	SimaPro	All 18 ReCipe Midpoint impact categories; 3 ReCipe endpoint damage categories; cumulative energy demand	×	√
Giani et al. (2015)	P-LCA	Key processes: Company survey; Upstream processes: Ecoinvent database; published literature	SimaPro 7.3	All 18 ReCipe Midpoint impact categories	×	√
Oliver-Sola et al. (2009)	P-LCA	Ecoinvent 1.2 database	EcoConcrete LCA tool	Abiotic depletion potential, Acidification potential, Eutrophication potential, Global warming potential (GWP), Human toxicity potential, Ozone layer depletion potential, Photochemical ozone creation potential	×	√

Studies	Method	Data sources	Tool	Output/Impact categories	Sensitivity	Uncertainty
Chiu et al. (2008)	P-LCA	Eco-indicator 99	-	Energy sources, Resources	×	×
Chowdhury et al. (2010)	P-LCA	Published literature; CMLCA	CMLCA	Acidification potential, Aquatic ecotoxicity potential, Aquatic sediment ecotoxicity potential, Energy consumption, GWP, Human toxicity potential, Terrestrial ecotoxicity potential	×	×
Huang et al. (2009)	P-LCA	Published literature and publications	VISSIM, EnvPro	Acidification, Eco-toxicity, Eutrophication, Global warming, Human toxicity, Photo-oxidant formation	×	×
Loijos et al. (2013)	P-LCA	Published literature and LCI databases	-	GWP	√	×
Yu and Lu (2012)	P-LCA	Portland Cement Association; Swedish Environmental Research Institute	-	Energy (Primary and feedstock), GHG (CO_2, CH_4, N_2O, VOC, NO_x, CO, PM_{10}, SO_x)	√	√
Birgisdottir et al. (2007)	P-LCA	-	ROAD-RES model	Acidification, Ecotoxicity in water/soil, Global Warming, Human Toxicity via air/water/soil, Nutrient Enrichment, Photochemical Ozone Formation, Stored Ecotoxicity to water/soil, Stratospheric Ozone Depletion	√	×

Studies	Method	Data sources	Tool	Output/Impact categories	Sensitivity	Uncertainty
Olsson et al. (2006)	P-LCA	-	-	Emissions to air (SO_2, NO_x, CO, CO_2, HC, CH_4, VOC, N_2O, and particles) and water (COD, N-tot, Oil, Phenol, As, Cd, Cr, Cu, Ni, Pb, and Zn), Resources use (natural aggregates, energy)	√	×
Jullien et al. (2006)	P-LCA	-	-	Odors, PAH, VOC	×	×
Anastasiou et al. (2015)	P-LCA	-	SimaPro 7.1	GWP_{100}, Resource use	√	×
Farina et al. (2017)	P-LCA	-	SimaPro 7.3	17 ReCiPe midpoint categories; 3 ReCiPe endpoint damage categories	×	×
Cass and Mukherjee (2011)	Hybrid	Site investigation using FieldManager	SimaPro 7, EIO-LCA, e-CALC	CO_2 emissions	×	×
Tatari et al. (2012)	Hybrid	Published literature and report; National Renewable Energy Laboratory LCI database	-	CH_4, CO, CO_2, N_2O, PM, SO_2, Cumulative mass, Ecological cumulative exergy consumption, Energy, Industrial cumulative exergy consumption	√	√

Studies	Method	Data sources	Tool	Output/Impact categories	Sensitivity	Uncertainty
Treloar et al. (2004)	Hybrid	Published literature	-	Energy	×	×
Aurangzeb et al. (2014)	Hybrid	-	-	Energy consumption, GHG emissions (CH_4, CO_2, N_2O)	×	×
Santos et al. (2017)	Hybrid	-	EIO-LCA model	Acidification air (AC), Eutrophication air (EU), Human health criteria pollutants (HH), Photochemical smog formation (PSF)	√	√
Roth and Eklund (2003)	-	-	-	-	×	×
Carpenter et al. (2007)	-	-	PaLATE, HYDRUS2D	CO, CO_2, NO_X, PM_{10}, SO_2, Energy, Hg, HTP (Cancer), HTP (Non-cancer), Pb, RCRA HazW Gen, Water	×	×

Notes:

1. - – not specified; √ – included; × – not included;

2. Highly cited means twenty most cited papers and two recent highly cited publications with more than 10 citations.

Appendix D. Overview of key findings on the contributions of different life cycle phases

Studies	Location	Phases						Analysis Period (years)	Results
		Material production	Transportation	Construction	Use	M&R	EOL		
Cass and Mukherjee (2011)	US	√	×	√	×	×	×	-	**Materials, equipment, and fuel production**: 90%–94% of the CO_2 emissions; Equipment use and transportation: 6–10%
Santos et al. (2015)	Portugal	√	√	√	√	√	√	40	**Materials and usage phases**: major contribution to overall environmental impacts (low-volume traffic roads: materials phase contributes the most; high-volume traffic roads: usage phase dominates)
Loijos et al. (2013)	US	√	×	√	○	√	√	40	Year one generates the **majority of emissions** (materials production, pavement construction)
Kayo et al. (2015)	Japan	√	√	√	×	×	×	-	**Raw material procurement** - 88%; Material production - 7%; Transportation - < 1%; Construction: 4%
Kang et al. (2014)	US	√	√	√	×	×	×	-	The energy consumption and GWP in the **material phase** is remarkably higher than in the construction phase.
Mendoza et al. (2012)	Spain	√	×	√	×	×	√	> 45	**Construction materials** have the highest environmental impact (48–87%)

				Phases				Analysis	
Oliver-Sola et al. (2009)	Spain	√	√	√	×	√	○	45	Main contributor: **cement production** (especially clinker)
Weiland and Muench (2010)	US	√	√	√	×	√	×	50	**Material production** (cement, asphalt, HMA, PCC) dominates all impact categories
Yu and Lu (2012)	US	√	×	√	√	√	√	40	**Materials, congestion, and usage** contribute the most to air emissions and energy consumptions
Chen et al. (2016)	US	√	×	√	√	√	√	20, 40	**Material module, usage module**: two dominators
Choi et al. (2016)	US	√	√	√	×	√	√	50	**Cement manufacturing:** top-contributing sector
Mazumder et al. (2016)	US	√	√	√	√	√	×	50	**Material phase**: 97% of overall human toxicity in water (asphalt)
Araujo et al. (2014)	-	√	×	√	√	√	√	20	The energy consumption of the **use stage** is about 700 times higher than that of the construction phase

Notes:

1. √ – included; ○ – limited consideration; - – not specified; × – not included;

2. Highly cited means twenty most cited papers and two recent highly cited publications with more than 10 citations.

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