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Comprehensive review on greenhouse gas emission assessment over the full life-cycle of pavement

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ABSTRACT

Recent studies on pavement greenhouse gas (GHG) emissions have developed and applied various calculation methods and pavement life-cycle assessment (LCA) tools for different research objectives, phases included and assessment levels, exhibiting trade-offs in applicability, accuracy, and data availability. This study systematically reviews studies on pavement GHG emission sources and calculation methods, focusing on complex and controversial features. Pivotal questions including how different research objectives affect the choice of calculation methods, how the vague end-of-life of pavements affects the construction of calculation methods and the effect of uncertainty are explored. These present opportunities for further research. This study emphasizes the accuracy and generalizability of various research objectives and scenarios, aiming to provide a comprehensive reference for the conduct of the life-cycle inventory in pavement life-cycle assessment. It will help policymakers, the transportation sector, and other stakeholders in making more effective decisions on road sustainability, thereby contributing to the goal of net-zero emissions.

1. Introduction

The accumulation of greenhouse gas (GHG) due to human activities has heightened global warming concerns, prompting increasing attention. As a response, numerous countries have reached a consensus to mitigate climate change, leading to the formation of some international agreements and more ambitious net-zero emission targets [1,2]. The transportation sector, a significant contributor to GHG emissions [3], accounts for about 29 % of the U.S. total [4]. Similarly, the road transportation sub-sector in the European Union (EU) contributes approximately 77 % of the 27 EU countries' carbon emissions [5].

As a resource-intensive system, road infrastructures generate large but vague GHG emissions over the life-cycle. However, these impacts are often broadly attributed to "industry" and "electricity", according to the energy consumed by different phases, subjects, and construction results. Road construction and maintenance, part of the building industry, generate significant GHG emissions. Moreover,

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indirect emissions from the exposure of roads to the environment and intensive interactions with vehicles should not be ignored. The comprehension and assessment of GHG emissions from road infrastructure are still premature, hindered by the long life-cycle, regional variations, intricately involved elements, and significant uncertainty. Nowadays, the global road infrastructure still confronts substantial demands of maintenance and expansion, significantly contributing to GHG emissions. As noted by the European Automobile Manufacturers' Association (ACEA), intelligently designed, well-built, and well-maintained roads are key to further reducing road transportation CO_2 emissions [6,7]. Therefore, precise assessment of GHG emissions is crucial to guide emission reduction strategies and achieve net-zero emissions in the transportation sector.

Usually, road infrastructure includes various components such as facilities, structures, and electrical systems, with pavement being a critical category. Subject to vehicle loads and environmental impacts, pavements significantly affect traffic service quality and incur substantial direct or indirect GHG emissions through frequent maintenance and rehabilitation across the life-cycle. This study adopts the Systematic Literature Review (SLR) approach to systematically review the research on pavement GHG emission sources and calculation methods, focusing on complex and controversial features to provide sustainability references for pavement facilities with different stakeholder perspectives. Existing studies have examined pavement GHG emissions in full life-cycle sources and reduction technologies [7,8], the environmental impacts of pavement recycled material [9], and the implementation of pavement LCA [10–13]. Inspired by this, this study focuses on the inventory analysis step in LCA, examines calculation methods with different adaptability and accuracy for each phase of pavements, and explores key issues including how different research objectives affect the choice of calculation methods, how the ambiguous life of pavements affects the construction of calculation methods, and the impact of uncertainty. It provides guidance for the development of calculation methods and emission reduction technologies at different phases in the future.

2. Systematic literature review

2.1. Introduction of research method

This study reviews extant studies to answer an overarching research question: how can GHG emissions from the full life-cycle of pavements be scientifically calculated in different regions, for different research objectives, and under different scenarios? Six additional research questions are proposed to respond to the characteristics of pavements that distinguish them from other infrastructures:

- What calculation methods have been employed in different phases of pavement studies?
- How do different research objectives affect the choice of calculation methods?
- How does the vague end-of-life of pavements affect the construction of calculation methods?
- Where do the uncertainties in the calculation methods for GHG emissions in existing studies come from?

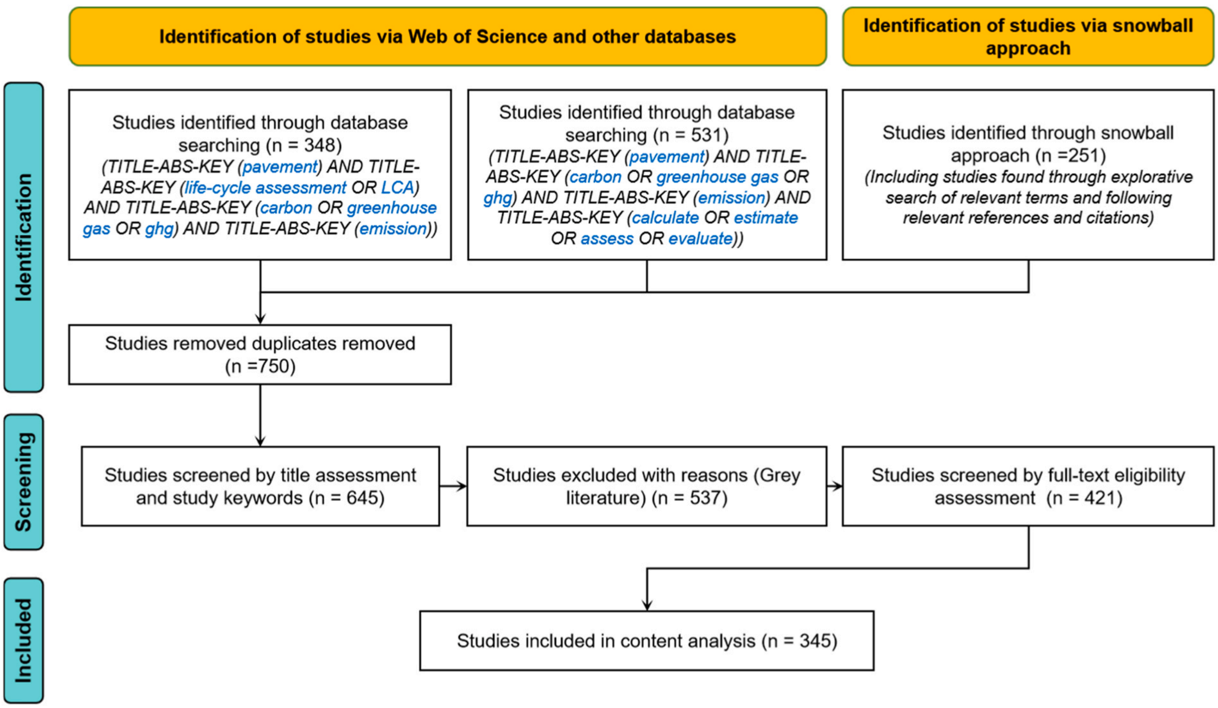

Fig. 1. Method for the literature search.

- What are the characteristics and applicability of databases, software and tools commonly used in research and application of life-cycle assessment of GHG emissions from pavements?
- What are the implications for the selection of emission reduction measures?

To answer these questions, this study selects the Web of Science database as the primary source based on the structured procedure of SLR and snowball approach, supplemented by other databases for information retrieval, and searches for relevant literature through a combination of the following keyword strings: 1) "pavement", "life-cycle assessment" or "LCA", "carbon or greenhouse gas or GHG", and "emission"; 2) "pavement", "carbon or greenhouse gas or GHG", "emission" and "calculate or estimate or assess or evaluate" [14]. All retrieved documents were reviewed to remove duplicates and filtered using several exclusion and inclusion criteria to obtain an acceptable final study scope. The screening criteria for literatures was the research relevance focus to the topic of this study, including the sources of GHG emissions over the full life cycle of road infrastructure, the analysis of responsibility for emissions, as well as the issues related to the measurement and reduction methodologies to indicate/improve GHG emissions and even sustainability performance. As shown in Fig. 1, the specific screening process involved 3 steps: 1) an initial relevance screening based on the study titles and keywords 2) the exclusion of gray literatures including conference papers, reports and any other informally published documents from the review scope to ensure the authority and accuracy of the review; and 3) a full-text assessment of the remaining papers for eligibility, ultimately retaining 345 papers. During the literature collection process, in order to avoid literature selection bias, two researchers respectively selected literature for review strictly based on the topic of the study, including both keyword searches and the snowball method, and conducted cross-checking when collecting literature.

2.2. *Pavement life-cycle greenhouse gas emissions sources and estimation methods*

The cradle-to-grave life-cycle of pavement can be divided into six phases, as shown in Fig. 2: material production, transportation, construction, use, maintenance and rehabilitation (M&R), and end of life (EOL) [15,16]. The sources of GHG emissions and assessment methodologies in existing studies at each phase are individually reviewed according to the chronology of the life-cycle.

For infrastructures such as pavement, which involve multiple phases in the full life-cycle, GHG emissions are associated with numerous industrial processes and interactions with the external environment, resulting in difficulties in data acquisition. Therefore, estimates of GHG emissions are challenging through direct measurements. However, various types of assessment methods are also constrained by their accuracy, applicability, and time sensitivity [17]. Notably, the detailed discussion of estimation methods for each phase in this study is not intended to promote the development of a complete LCA model, given the inherently limited applicability of differing functional boundaries with different objectives and scopes. Instead, this study is more interested in providing references for the development of accurate assessment of GHG emissions from pavement over the full life-cycle and further emission reduction strategies, or even facilitating studies targeting specific phases.

2.2.1. *Material production phase*

The material production phase specifically includes raw materials extraction and manufacture, resulting in embodied carbon, which significantly contributes to GHG emissions [18]. The emission factor approach is the most widely used carbon accounting

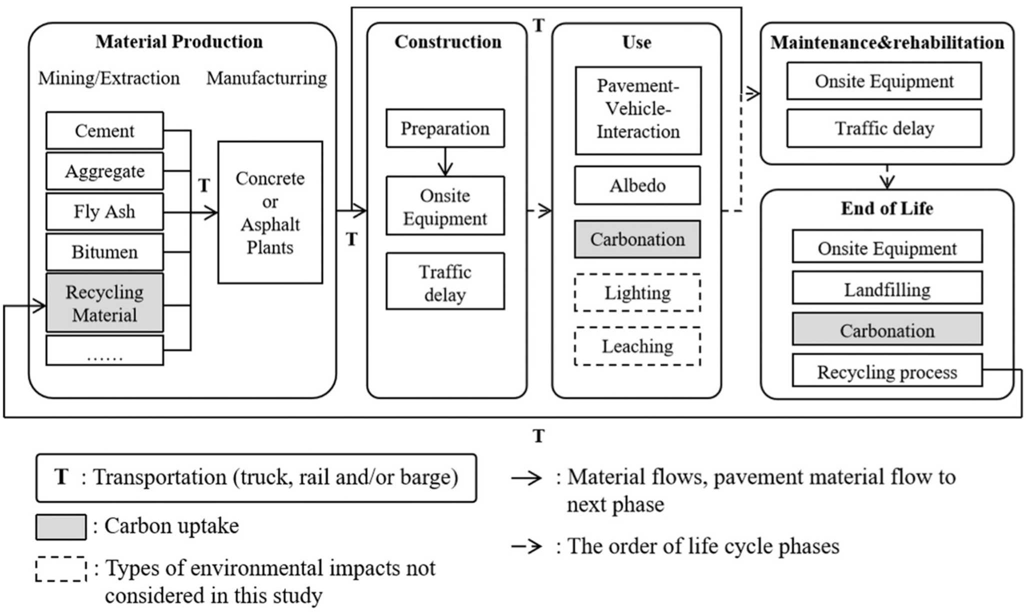

Fig. 2. life-cycle of the pavement.

method in various industries due to its simplicity, based on the basic equation provided by the IPCC (Intergovernmental Panel on Climate Change):

$$GHG\ emission = \sum Activity\ data \times Emission\ factor \tag{1}$$

Where the activity data is data on the level of activity that affects GHG emissions (mass/volume/kWh/km/etc.); and emission factors are coefficients that specify the amount of GHG emitted per unit of GHG-producing activity ($kgCO_{2e}$ per unit).

Emission factors include two categories: mass-based and task-based. Mass-based emission factors are associated with energy categories, such as GHG emissions per unit quantity of diesel consumed by asphalt mixing machinery. Pavement materials production involves multiple processes and value chains, and task-based emission factors, which are developed through environmental life-cycle analysis, are more convenient for assessing specific types of products or processes. Inspired by IPCC guidelines (For CO_2 uptake calculations, the IPCC classified methodological approaches into three tiers based on the quantity of information and calculation accuracy) [19,20], this study uses a tiered approach by summarising emission factors and their corresponding activity data used in existing studies with different levels of accuracy and requirements for the availability of activity data (emission factors' accuracy decreases gradually). As shown in Table. 1, at material production phase, emission factors are divided into three categories:

(1) Emissions per unit quantity of energy consumed (mass-based):

This type of emission factor strictly follows the chemical or mass balance reactions of the fossil fuel combustion process and is therefore not restricted to specific industrial technologies or material types, but is more broadly applicable and intrinsically calculable. IPCC or other agencies provide reference values for calorific values of major energy types and GHG emissions per unit of mass or volume of energy consumed, which can be used for the direct selection of such emission factors. The corresponding activity data is derived from the fuel consumption of the material extraction and manufacturing plants. In reviewed studies, Peng et al. [21] developed a model for calculating GHG emissions from asphalt pavements based on emission factors for diesel, coal, and heavy oil provided by IPCC, with activity data from a survey of carbon emissions from highways in several provinces in China. Tang et al. [22] chose the energy consumption (in terms of energy) required for the production of each type of material obtained from previous literature as the activity data, and the GHG emissions from typical energy resources in China as the emission factors. However, the complex stakeholders and processes involved in the material production phase pose challenges to accurately recording activity data, especially for higher-level estimations. During the feasibility or design phase, the availability of activity data introduces further uncertainty. These collectively limit the widespread adoption of such emission factors.

(2) Emissions per unit of material production (task-based):

The production of materials, i.e. the amount of material required for pavements, is notably more available as its corresponding activity data, both for pavements that have been constructed and are in the design phase. This improves the

Table 1
Summary of representative studies: types of material phase emission factor (EF), activity data (AD), and sources.

Emission Factor	Source of EF	Activity Data	Source of AD	Source	Applicability
I	IPCC	Quantity of energy consumed	—	[21]	• Highly accuracy • Suitable for situations where field data are available.
	GHG emissions of typical energy resources in China	Quantity of raw materials	Pavement Design	[22]	
II	Inventory of Carbon and Energy (ICE)	Material quantity	Bidding information	[30]	• EF are easy to obtain • Suitable for pre-design estimation or comparison of results between the same regions
	Estimation based on real-life data from material manufacturers		Pavement structure information	[31]	
	GaBi and CLCD database			[23]	
	Previous literature [32,33]			[34]	
	India construction materials database of embodied energy and GWP			[35]	
	Available literature specific to the Italian context and Eurobitume datasets			[36]	
	Previous literature[37–40]			[41]	
	Eurobitume and CLCD database, and previous literatures [42,43]			[44]	
III	EF for each region are calculated on the basis of previous literatures [28,45]	Pavement length	Regional road network information	[27]	• Limited accuracy • usually used for macro-assessment at the region level.
	Cement production process			[29]	
	Calculated by accumulating the emissions from different processes/ materials	Road volume		[46]	

Note: I, II, and III indicate the 3 tiers of emission factors units elaborated in the text, where
I: GHG emission per unit quantity of energy used.
II: GHG emission (or energy consumed) per unit quantity of material produced.
III: GHG emission per unit of pavement length or volume.

generalizability of this type of emission factor in the development of GHG emission calculation methods and LCA models, which have been widely used in many studies. Cong et al. [23] obtained the various GHG emissions from the production of 1 kg of various pavement materials as well as the exploitation and refining of 1 kg of energy according to the GaBi and Chinese Life Cycle Database (CLCD) databases. Similarly, referring to peer-reviewed literature and published research reports, Liu et al. [24] selected emission factors with a complete and detailed analysis process and precise calculations, expressed as emissions per unit amount of material produced. Nascimento et al. [25] obtained the number and type of materials required for the pavement based on the mechanistic-empirical design method, and the emission factors for each type of material were obtained from Simapro software and the Ecoinvent database. The accessibility of material production data, encompassing the quantity of materials necessary for pavements, is significantly higher, providing corresponding activity data for both constructed pavements and those in the design phase. This enhances the applicability of such emission factors in the formulation of GHG emission calculation methodologies and LCA models, which have found widespread adoption across numerous studies. The emission factors are inherently showing significant regional differences and time sensitivity, due to differences and advances in production technologies and different system boundaries defined in different data sources. This makes comparisons between different regions difficult. Wang et al. [26] summarized the primary energy consumption (MJ/kg) for the production of 1 kg of the main material for pavements provided in different data sources including the asphalt inventory produced by EcoInvent, the U.S. life-cycle Inventory (USLCI) produced by the National Renewable Energy Laboratory, and some other data sources. And the difference in their energy requirements can be up to 87 %.

(3) Emissions per unit length or volume of pavement (incorporating multiple materials in the pavement structure) (task-based):

Pavement design and production techniques in the same region generally follow the same standards, which provides the possibility of a rough estimation of GHG emissions of the road network from a larger region and at a higher level. But also for this reason, there are almost no available databases from which to choose directly. Many studies integrate emission data from various local sectors, applying emissions from the production of a unit length or volume of pavements as the emission factor and the road network inventory as the corresponding activity data. For example, Yu et al. [27] calculated and established emission factors for the construction phase of road structures in each province and region based on the carbon emission factor data established by Zhao et al. for sampling cement production lines [28], thus establishing a regional road construction GHG emission calculation model as a function of road length. The model developed by Chen et al. [29] calculates the GHG emissions from road construction in each province as the GHG emission factor for each type of road multiplied by the length of the road in each province to obtain the cumulative GHG emissions for all. These characteristics result in limited accuracy of GHG emission estimates, which are typically used at provincial and regional level road network emission assessments.

2.2.2. Transportation Phase

The transportation phase involves the movement of pavement materials before being put into service, including the transportation of materials from collection sites to processing plants, from processing plants to construction sites, and the removal of recycled materials away from the site during the EOL phase. From the full life-cycle perspective, the transportation phase has received relatively

Table 2
Summary of studies: types of transportation phase emission factor, activity data and sources.

Emission Factor	Source of EF	Activity Data	Source of AD	Whether to consider no-load	Source	Applicability
I	The Climate Registry database and engine certification data provided by the EPA	• Time in and out of sites • Miles travelled • Diesel fuel used	Truck driver reports	—	[47]	• Highly accuracy • Suitable for situations where field data are available.
	Publicly available approximate estimate norm of highway project	• Hourly diesel or gasoline consumption • Operating time of vehicles	Highway Administration Bureau of Zhejiang Province	—	[24]	
II	MOVES	Transportation distance Quantity of materials	—	—	[48]	• EF are easy to obtain • Suitable for pre-design estimation or comparison of results between the same regions
	Chinese standards	Transportation distance	Reasonable assumption	—	[49]	
	—			—	[36]	
	Quota method			—	[23]	
	MOVES			—	[50]	
	—			√	[51]	
	—			√	[52]	
	—		—	√	[53]	

Note: I and II indicate the 2 tiers of emission factors units elaborated in the text, where
I: GHG emission per unit quantity of energy used.
II: GHG emission (or energy consumed) per unit transport task.

limited attention in existing studies, many of which categorize it as part of the material production or construction phase. The subject of GHG emissions in the transportation phase are the vehicles used to transport the pavement material, and the energy consumption of vehicle operation directly generates GHG emissions. As shown in Table. 2, the selection of the emission factors, whether mass-based or task-based, revolves around the vehicle's operation.

(1) Emissions per unit quantity of energy consumed

Activity data, derived directly from energy consumption records, represent the actual energy consumed during transportation activities, require a high degree of data accessibility, and rely on project-specific information collection dedicated to site conditions. For example, Liu et al. [47] recorded the time in and out from the job site, the total mileage travelled, and the diesel used by each truck, based on truck driver reports and applied them to estimate the GHG emissions of the trucks when transporting materials. Liu et al. [24] calculate GHG emissions during the transportation phase based on data on the use of vehicles provided by the Highway Administration of Zhejiang Province, China, and the hourly energy consumption of transport vehicles obtained from publicly available approximate estimate norm of highway project. Such activity data may be potentially accessible for individual road projects; but for broader GHG estimation purposes, it proves challenging due to the impracticality of accurately recording energy consumption across larger-scale road construction endeavours.

(2) Emissions per unit transport task

The transportation of materials is influenced by engine technology, the payload capacity, the distance and speed travelled, and the quality of transported materials [54]. The corresponding activity data is the number of tasks operated by vehicles, like transportation time or distance, which is the most commonly used method in existing studies and provides an indirect but practical way to estimate energy consumption during the transportation phase.

Where direct energy consumption data are challenging to acquire, material transportation routes are typically predetermined [55] and therefore many studies estimated haul distances and the number of trips reasonably through actual site visits to the location of the plant site, material stockpiles, water source, and disposal site [48–50]. For typical vehicles, task-based emission factors are more readily available in various local databases. It is worth noting that the payload capacity of the vehicle significantly impacts energy efficiency, exemplified by the difference in energy consumption between a fully loaded vehicle and an empty one during a round trip for material transportation, ignoring it will lead to inaccurate calculation results [53]. Many studies now take this into account [42,51, 56]. Wang et al. [56] observed that energy consumption differences between fully loaded and unloaded trucks could range from 21 % to 29 %.

2.2.3. Construction phase

GHG emissions in the construction phase arise from the energy consumed in the operation of construction machinery. In addition, some studies extend their consideration to site preparation, such as changes in carbon stocks due to the removal of biomass, dead organic matter and soil [30]. GHG emissions generated during the construction phase are similar in essence to those generated during the transportation phase, as emissions result from the energy consumption of mechanical operations. Consequently, their calculation methodologies exhibit similar characteristics. However, there is a difference in the activity data regarding its availability, collection and organization methods, as delineated below: 1) the workload of diverse equipment during the construction phase can be reliably estimated based on the pavement design plan. For example, Kim et al. [31] estimated the working hours of the equipment used in the earthwork activities based on final design documents, which fully define the construction project; 2) the operational schedule and duration of construction machinery are affected by the construction processes and sequence, often leading to inevitable periods of idle time. As a result, the total construction working hours may not adequately reflect the effective operational time of the equipment. To address this problem, Liu et al. [47] introduced the utilization percentage to rule out the time for idling and moving.

2.2.4. Use phase

As the longest phase of the pavement life-cycle, many factors will influence GHG emissions: pavement prosperities affects vehicle fuel economy through pavement-vehicle interaction (PVI); maintenance and rehabilitation activities contribute to GHG emissions, similarly to the construction phase; pavement albedo has the potential to mitigate the greenhouse effect; and carbonation of concrete pavements leads to carbon uptake, providing environmental benefits [57]. The use phase contributes a substantial proportion of GHG emissions, especially for high-volume roads [58]. When the AADT reaches 10,000, more than 97 % of life-cycle GHG emissions will be released during the use phase, with less than a 1 % difference between alternative designs [30]. Some European studies have quantified this rate as 93–99 % or even higher [59]. Due to the limitations of the LCA inventory impact assessment methodology [13], many of the early studies did not include the use phase in system boundaries. Diverging from the preceding phases, the use phase involves a variety of factors and mechanisms, and its GHG emissions come more from indirect emissions resulting from the interaction of the pavement with road users or the environment. This makes traditional methods, such as emission factor methods, often no longer valid during the use phase. In this section, the calculation methods, including both more complex model estimations based on underlying mechanisms and widely adopted simplified models, are mainly discussed to provoke thought and encourage further research. Previously, factors of interest are those intimately associated with the pavement itself during the life-cycle, so 1) road lighting and leaching are excluded, as the former is less crudely categorized as part of the pavement and the latter's environmental impact is not reflected in GHG emissions; and 2) the system boundary for vehicle emissions due to traffic delays and pavement properties deterioration only includes extra emissions due to the reduced fuel economy.

(1) Pavement-Vehicle-Interaction (PVI)

Deterioration of pavement properties influences vehicle fuel efficiency, leading to extra GHG emissions, which are realized through pavement-vehicle interaction (PVI) [60]. The increase in rolling resistance caused by the deterioration of the pavement properties during the use phase necessitates compensatory engine power from vehicles, which leads to additional energy consumption and GHG emissions. Although the influence on rolling resistance can predominantly be attributed to various factors related to vehicle tyres, pavement properties play an integral role. The resulting extra energy consumption can account for 15–50 % of the vehicle's total energy consumption, depending on its speed [61].

In existing studies, three pavement properties that are commonly considered to affect vehicle rolling resistance are pavement texture, roughness (i.e., smoothness) and deflection. As shown in Fig. 3, pavement roughness and macrotexture are deviations of the pavement surface from a true planar surface, resulting in vibrations in the tyres and vehicle suspension, which are absorbed by the vehicle's shock absorbers and tyres, leading to energy losses in the entire vehicle system. The International Roughness Index (IRI) is often used as the metric of pavement roughness. The calculations of Ziyadi et al. [62] show that one unit change of IRI results in an average increase in fuel consumption of 3 % and 2 %, respectively, at high and low speeds for passenger cars. Pavement texture is often expressed as mean profile depth (MPD, for asphalt) or mean texture depth (MTD, for concrete) [63]. For light vehicles, the impact of MPD is about three times the IRI effect [64]. Chatti and Zaabar [65] reported that excessive fuel consumption accounted for almost 4 % when the MPD changed from 0.5 mm to 3 mm. Deflection changes the pavement geometry and the pavement material viscoelasticity, leading to energy dissipation that must be compensated for by external energy sources, which were influenced by temperature, speed and pavement types. All three of these factors have a significant impact on PVI, but they do not share the same mechanisms and weights. Existing studies have investigated the mechanism of their effects on fuel consumption and developed calculation models for each of them. For example, some researchers have found and established a linear relationship between energy consumption and IRI (or change in IRI, ΔIRI) [60,66]. Louhghalam et al. [67] developed a mechanical model for estimating deflection-induced excessive fuel consumption and considered that deflection-induced excess fuel consumption is proportional to the square of the load. On this basis, Giustozzi et al. [68] evaluated the sensitivity of a deflection-induced PVI model used to quantify excessive fuel consumption.

Table. 3 summarizes the calculation methods of GHG emission induced by pavement properties. In order to briefly calculate the extra GHG emissions from vehicles due to PVI, many studies have used classical models that have been developed, which usually simplify the types of influence factors and mathematical relationships that are considered. The most widely used of these include the Highway Development and Management Model—version 4 (HDM-4) [69] and the model developed by the Swedish National Road and Transport Research Institute (VTI), within the European Commission project Miriam (Models for rolling resistance In Road Infrastructure Asset Management systems) [70]. HDM-4 includes a linear model for simulating rolling resistance with IRI, MPD, and an

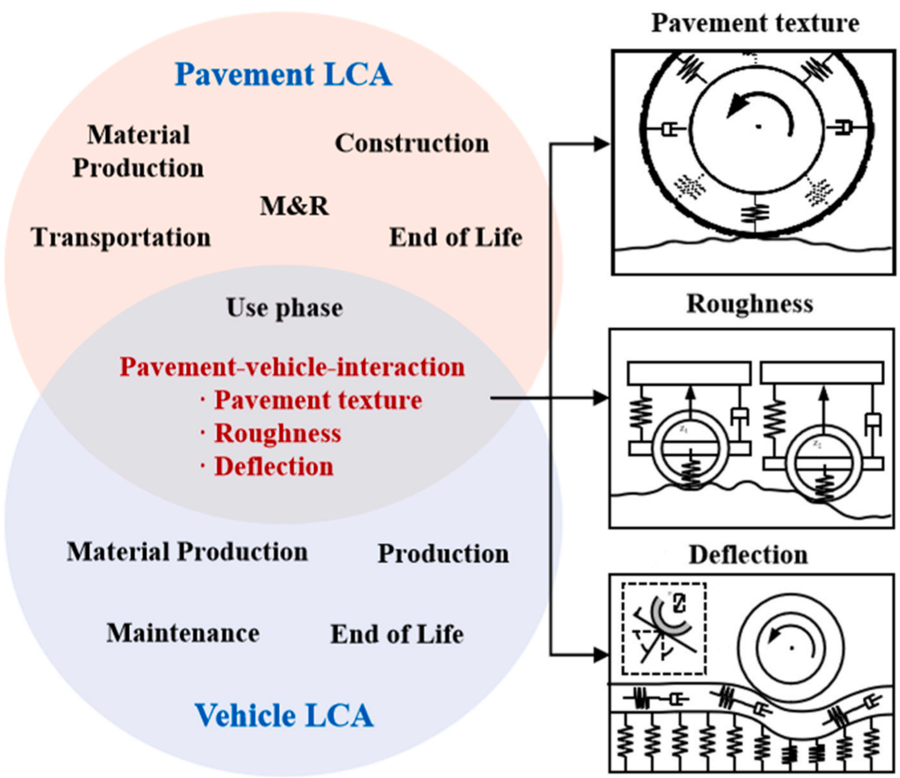

Fig. 3. Pavement-Vehicle-Interaction and its influencing factors in a joint pavement-vehicle life-cycle assessment framework [62].

Table 3
Summaries of studies: calculation methods of GHG emission induced by pavement properties.

Pavement Properties			Required other data	Features	Source
IRI	MTD/MPD	Deflection			
√	—	—	• AADT • Number of axles • Annual growth factor	HDM−4	[72]
√	—	—	• Design traffic for the assessment period • Length of road section • Adjustment of speed level Traffic-flow and gradient	Linear relationship between fuel consumption factor and ΔIRI.	[73]
√	—	—	—	Linear relationship between additional fuel consumption factor and IRI.	[71]
√	—	—	Vehicle speed	MOVES.	[51]
√	—	—	Regression coefficients	The coefficients in the formula are obtained from the regression.	[77]
√	—	—	• AADT • Traffic growth rate • Percent fuel increase per Δ*IRI* • Pavement length	Introducing extra vehicle kilometres to characterize extra fuel consumption due to the higher roughness.	[48]
√	—	—	• AADT initial value • Yearly traffic increase • Road lifespan • Lane distribution factor	Linear relationship between fuel consumption factor and IRI.	[52]
√	—	—	Vehicle speed	HDM−4 and MOVES	[62]
√	√	—	• Vehicle speed • Road curvature • Road slope	VTI	[54]
√	√	—	• AADT • Fuel consumption when the vehicle is driven on the pavement with specified IRI and MPD versus a typical smooth pavement	VTI and COPERTv5.0	[76]
√	√	√	• Coefficients determined by factors such as tyre type, climatic factors • Pavement properties coefficients of the HDM−4 model, vehicle mass, number of vehicles, and speed.	HDM−4 and MOVES	[26]
—	—	—	• Highway length • Cumulative traffic volume • Fuel economy of vehicle • Emission factors	Constant values were used to represent fuel economy.	[78]

engine model that links rolling resistance to vehicle fuel consumption. The model needs to be calibrated in a targeted manner to adapt it to the realities of use in each location. Similarly, the VTI model consists of a general rolling resistance model and a fuel consumption model: the first one is mainly based on empirical data from coast-down measurements in Sweden and incorporated into a driving resistance based energy consumption model. The fuel consumption model has been calibrated to the calculated values of the computer program VETO, which is a theoretical model developed by VTI to calculate fuel consumption and traffic emissions due to various characteristics of vehicles, roads and driving behaviour [64]. Similarly, many studies consider energy consumption as a simple linear model of pavement properties. For example, Barbieri et al. [52] ignored texture and deflection and used a simple linear model to approximate the effect of IRI. This simple relation is also used in studies of Zhang et al. [55] and Liu et al. [71]. Based on the HDM-4 model, Alam et al. [72] considered the additional fuel consumption of a single vehicle as a linear function of ΔIRI and input the vehicle load-related information, which was integrated over the analyzed period to derive the total additional fuel consumption. Similarly, Alam et al. [73] consider fuel consumption as a linear function of ΔIRI and regard the improvement effects generated by interventions such as pavement maintenance and traffic management. Chong and Wang [48] introduce the concept of extra vehicle kilometres to characterize the extra fuel consumption due to higher roughness, and the extra vehicle kilometres are linearly related to the ΔIRI. Some studies incorporate the effects of such as speed and curvature into calculations and integrate road traffic flow data. Santos et al. [54] used the VTI model, which considers the effect of pavement properties on rolling resistance to arise partly from changes in pavement roughness and macrostructure, considering road curvature and road gradient versus vehicle speed.

It can be seen that the consideration of pavement properties in existing studies is not complete: the three factors mentioned above are not captured exactly, which derives from their respective significance; and the relationship between pavement properties and extra GHG emissions or energy consumption is only shown to be simple linear or exponential. However, the mechanisms by which pavement properties affect emissions are complex and beyond what can be adequately represented by linear or exponential relationships. The results of Ejsmont et al. [74] showed that the difference in tyre rolling resistance due to texture is not linearly related to MPD due to the envelope effect of tyres on the pavement. How pavement stiffness affects PVI has not been consistently explained [64]. Besides, the rolling resistance calculated by widely used classical models for vehicle travelling speeds tends to be derived from steady speeds, is unresponsive to speed fluctuations in real traffic environments, and is unable to cope with improvements in vehicle operation and emissions over time [26]. Therefore, coupling the rolling resistance influenced by pavement properties, with a mature vehicle emission model to obtain more accurate emission calculations has also become a new research trend. In the study of Wang et al. [75], HDM-4 was used to estimate rolling resistance and MOVES was used to model vehicle emissions as a function of rolling resistance. Using HDM-4 to update the default rolling resistance coefficients in the MOVES database compensates for the fact that MOVES ignores the effect of pavement properties. Further, Ziyadi et al. [62] chose an incremental approach to estimate changes in energy consumption and emissions based on the two varying parameters coupled to one another: vehicle speed and IRI, simplifying the implementation of the pavement LCA utilization phase framework. Santos et al. [76] combined the VTI rolling resistance model with the COPERTv5.0 emissions model to correlate the effects of pavement properties on energy consumption and emissions using the effective AADT.

(2) Pavement Albedo

As a surface covering, pavement can reflect a fraction of the incident solar radiation into space, a property that can be characterized by albedo, i.e. the proportion of incident solar radiation that is reflected by the pavement, characterized by a dimensionless number ranging from 0 (totally absorbed) to 1 (totally reflected). High albedo pavements produce negative RF by reflecting a portion of the incident radiation into space, mitigating or delaying to some extent some of the consequences of warming due to CO_2 emissions [79]. Generally, there are two pathways by which pavement albedo affects climate impacts [79], as shown in Fig. 4: the first is by affecting direct radiative forcing (RF), which is quantified as the rate of change of the Earth's energy per unit area as measured at the top of the atmosphere [80]; and the second is by affecting the energy demand from neighbouring buildings. According to the research boundary, more attention is given to the effect of RF on the greenhouse effect in this study [81].

Yu and Lu [83] report that albedo effects significantly impact life-cycle inventory, reducing CO_2-equivalent emissions by 9.2 % for Portland cement concrete pavement but increasing them by 19.1 % for hot mixture asphalt pavement. Ghenai et al. [84] indicate that increasing pavement albedo from 24 % to 70 % across 81,000 m^2 of an educational complex could offset 28,350 tons of CO_2. The adjustment of pavement albedo to moderate the greenhouse effect and mitigate the urban heat island phenomenon is a distinctive attribute of cool pavement technologies, which are being widely researched and applied [85–87]. The primary factors affecting albedo include pavement type and age: initially, concrete pavements exhibit higher albedo, which tends to decrease slightly over time due to weathering, whereas asphalt pavements generally display the opposite trend [88].

The effect of pavement albedo on GHG emissions at different time scales was quantified by Akbari et al. [79]: for the short-term effect (25–50 years), each 0.15 increase in pavement albedo emits offset of 38 kg CO_2 m^{-2} emissions of paved area, while on a century, scale this offset can be as high as 4.90 kg CO_2 m^{-2}. The calculation of CO_2 offset per unit area due to albedo in some subsequent studies is also based on this, and a simple estimate of the impact of albedo is achieved by multiplying the change in albedo by an offsetting effect factor [66,84,89,90]. However, such a simple estimate ignores that the emissions offset associated with such a step change in RF would increase slowly with time. Furthermore, the results of the different time scale estimations are based on different but overlapping time spans, making it difficult to choose a reliable value for the pavement LCA [83]. Given this issue, some studies have introduced time-dependent parameters in estimating the albedo-induced CO_2 offsets. Changes in pavement albedo are considered in the general pavement LCA method created by Loijos et al. [91]: it decreases steadily from 0.4 to 0.25 during the use phase, but a constant value of −0.25 kg CO_2 is still applied. In the field of climate science, Bird et al. [92] established a time-dependent equivalence between the change in RF and CO_2-equivalent, as shown in Eq. (2), which is now also widely applied in the field of pavement [52,83, 93–95].

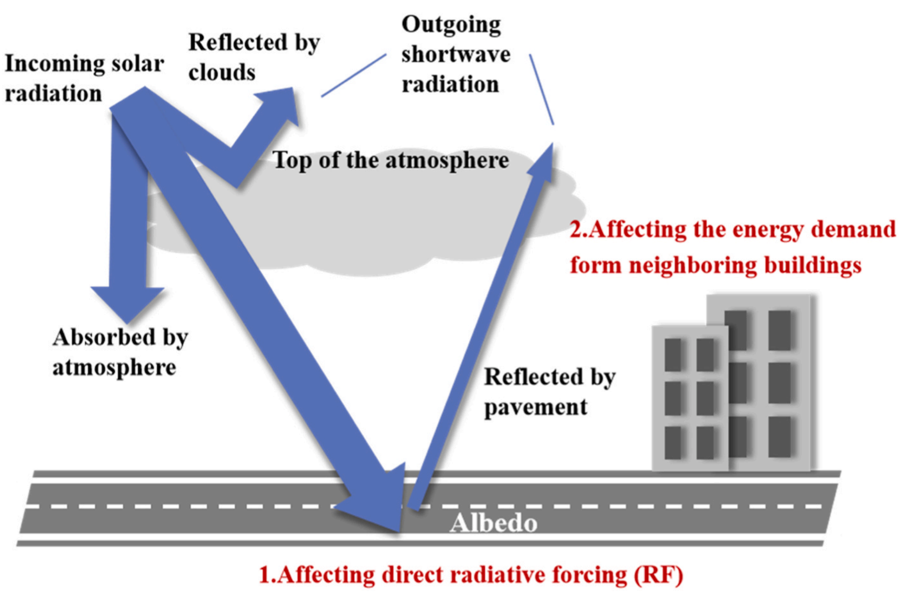

Fig. 4. Impact of pavement albedo on radiative forcing and building energy demand [82].

$$CO_2(t) = \frac{A \times RF \times \ln 2 \times P_{CO_2} \times M_{CO_2} \times m_{air}}{A_{earth} \times \Delta F_{2x} \times M_{air} \times AF(t)} \tag{2}$$

where A is the area affected by changes of surface albedo; RF is to be further linked to albedo; P_{CO_2} is the reference CO_2 partial pressure; M_{CO_2} is the molecular weight of CO_2; m_{air} is the total mass of atmosphere; A_{earth} is the surface area of Earth; ΔF_{2x} is the RF due to the doubling concentration of CO_2; M_{air} is the molecular weight of dry air; $AF(t)$ is a time-dependent, through which the time-dependent effect is assigned, and t is time (year). The effect of albedo on RF has been interpreted differently in various studies: Yu and Lu [83] and Susca [95] considered RF as a linear function of albedo; Muñoz et al. [93] and Xu et al. [96] established the relationship between RF and solar radiation, atmospheric transmittance factor and variations in surface albedo. Estimating the GHG reduction potential from albedo is challenging because its effect on the greenhouse effect is realized through indirect pathways rather than direct reductions in GHG emissions, which has led to little consideration of albedo in current studies, especially those focused on developing practical tools for assessment and calculation. However, its potential role in guiding pavement design and maintenance decisions to reduce GHG emissions and mitigate the greenhouse effect deserves attention. Besides, several new methods have been proposed. Xu et al. [81] introduced a high-resolution approach that uses both a coupled physical-simulation model and a machine-learning model to quantify the global warming impact changes attributed to cool pavements in an urban vicinity. Global climate models, which are widely used in geography and meteorology, are used to estimate the climate response of albedo on land or urban surfaces. Akbari et al. [97] used the University of Victoria Earth System Climate Model (UVic ESCM) to simulate the long-term (decadal to centennial) climate impacts of increasing urban surface albedos; Menon et al. [98] used the land component (CLSM) of the NASA GEOS-5 climate model to quantify the effects of changes in roof and pavement albedo on RF and temperature in urban areas; Oleson et al. [99] used the global climate model coupled with an urban canyon model to quantify the effects of white roofs on urban temperatures. Their estimation boundaries tend to be large and extensively consider climatic factors, so at the micro-scale they are not currently widely used in estimating local pavement albedo-induced effects yet still have the potential to be used in the estimation of road networks at the regional or national level.

(3) Carbonation

Carbon uptake is not a novelty in climate assessment [100]. However, this is a factor that has been overlooked in many road infrastructure studies, as concrete pavements can also act as carbon sinks [101,102]. Cement, an important component in concrete pavement material can reabsorb atmospheric CO_2 over time, a process termed carbonation, which is an intrinsic property of Portland cement-based concrete [103,104]. In addition, concrete additives such as blast furnace slag (BFS) and fly ash from coal combustion have the potential to absorb CO_2 as a strategy for CO_2 mineral sequestration [105,106]. Carbonation occurs during the long-term use phase of concrete pavements and the end-of-life phase when they are removed, crushed and landfilled or reintroduced into a new life-cycle as recycled material, as shown in Fig. 5. Although the process of carbonation is difficult to calculate because it covers a long period, and involves many factors, it still deserves attention as an offset for upfront GHG emissions, as it is a necessary step towards net-zero emissions.

The maximum uptake depends on the cement content, but various environmental factors influence the actual carbon uptake. Simplified calculation methods are based on fixed conservative values, such as Sanjuán et al. [107] and Zhang et al. [108] used a fixed CO_2 uptake rate for a rough estimation. For more accurate real-time calculations, the most widely used model based on Fick's law of

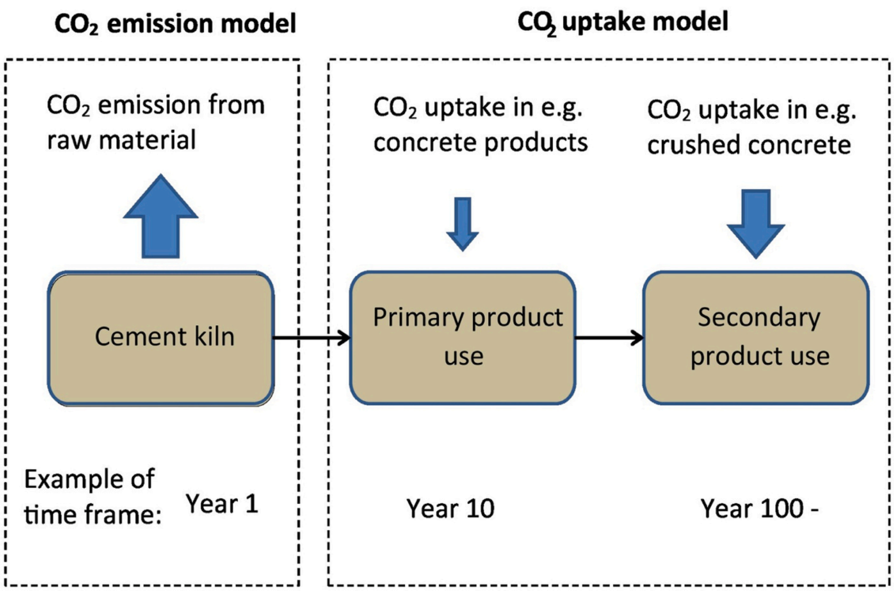

Fig. 5. CO_2 balance in cement products over a certain period [100].

diffusion allows the calculation of carbon uptake per unit of surface area for a certain period through the formula Eq. (3) [109]:

$$CO_2\text{uptake at a surface} = k\sqrt{t}\cdot C\cdot f_{CaO}\cdot\gamma\cdot M_r \tag{3}$$

where $k\sqrt{t}$ is the carbonation depth, which is calculated based on Fick's law of diffusion using carbonation rate coefficient k and the exposure time t, with k dependent on the compressive strength class and exposure conditions, cement additives, CO_2 concentration and coating and cover; C is clinker to cement ratio; f_{CaO} is the average CaO content of clinker in cement; γ is the proportion of CaO within fully carbonated cement that converts to $CaCO_3$, and M_r is the ratio of carbon element to CaO [110]. In addition, Lagerblad [109] defined the rate and degree of carbonation as tabular values based on concrete strength classes (cylinder) and exposure conditions, which can be directly selected for simple calculations [100,104]. This calculation method is widely used in existing studies [10,66].

However, there are some gaps in existing widely used methods: calculation methods based on Fick's law of diffusion are often better suited for individual projects and present challenges in estimating carbon sequestration at the network level; the consideration of pavement design heterogeneity and precise characterization of the pavement network is missing; there is regional variability in the design of pavements and materials used; and existing studies tend to analyze pavements from the cradle period, and frequent maintenance and rehabilitation faced by pavements after construction is often overlooked. In response to the above, AzariJafari et al. [101] made a new attempt and developed a bottom-up method to assess the carbon uptake of the US pavement network in the next 30 years. To this end, a pavement management system (PMS) model was developed to estimate pavement ages and the quantity of concrete removed using local maintenance practices. Then a carbon uptake model, sensitive to mix design components and ambient conditions, was adapted and integrated into this system model and use a novel dynamic material flow analysis framework to analyze the CO_2 abatement cost for different stockpiling timeframes.

In building sectors, carbonation is seen as a factor contributing to the degradation of reinforced concrete, due to corrosion of the steel, but this does not apply to roads. Additionally, the emission reduction from carbonation plays out more after the end of life, as the specific surface area of the material increases [111]. This provides additional environmental benefits for the use of recycled materials, beyond the reduction in virgin material use. Therefore, there is significant potential to consider carbonization as an emission reduction measure.

2.2.5. Maintenance and rehabilitation phase

During the long life-cycle of pavement, constructed pavements face problems such as deterioration and ageing. To maintain the in-service pavement performance within satisfactory limits, several M&R activities are inevitably required during the use phase. CO_2 emissions from maintenance account for 1/3 of the full life-cycle emissions, and even more than new construction [50,112,113].

Regardless of the type of maintenance strategy, the sources of GHG emissions during the M&R phase can be divided into maintenance activities and traffic delays due to work zones. M&R activities can be considered as repeated pavement construction events and often necessitate work zones that close lanes and decrease network capacity, leading to traffic delays and additional user emissions. These emissions are challenging to quantify accurately due to the complexities of traffic environments, site conditions, and road grades [114]. In urban areas and motorways with high AADT, emissions from traffic delays are significant, prompting road management to

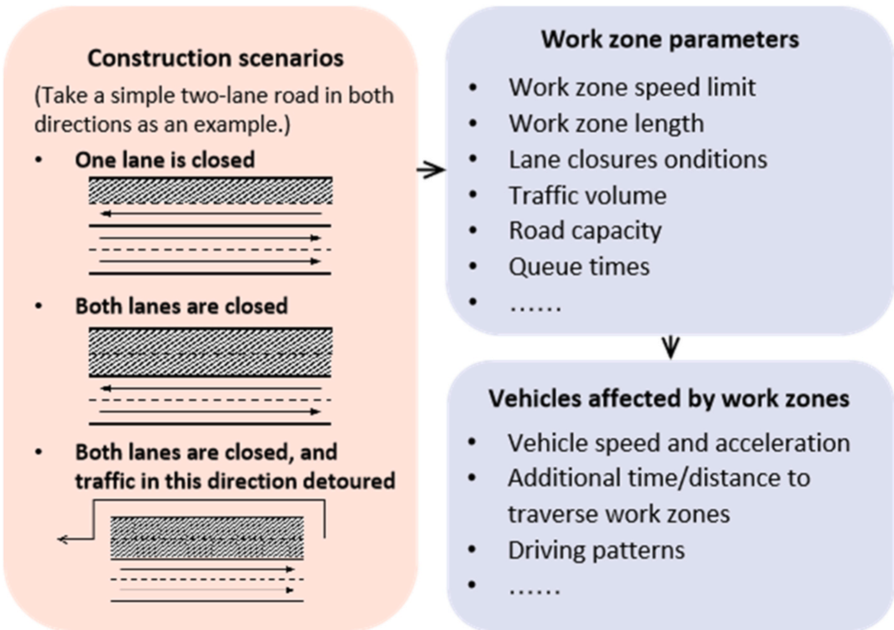

Fig. 6. Traffic delays caused by work zones.

integrate work zone management into maintenance decisions.

For the work zone, user emissions are associated with both free-flow and forced-flow conditions. Under the free-flow condition, vehicles decelerate from upstream speeds to work zone speeds, pass through the work zone at reduced speed, and then accelerate back to the initial speed. In contrast, when traffic demand exceeds the capacity of the work zone, traffic flow is interrupted and vehicles queue. In both cases, the additional contribution to GHG emissions is in the additional energy consumption that occurs when vehicle speeds change, idling delays due to stop-and-go queuing, and detouring delays for the additional distance travelled around the work zone [30]. Several types of delays can occur in this process [51,115]:

(1) Speed change (deceleration or acceleration) delay

Speed change delay is the additional time necessary to decelerate from the upstream approach speed to the work zone speed and then accelerate back to the initial approach speed after traversing the work zone.

(2) Reduced speed delay

Reduced speed delay is the additional time necessary to traverse the work zone at the lower posted speed, mainly depending on the upstream and work zone speed differential and length of the work zone; this also includes the reduced speed delay in queue under forced-flow conditions.

(3) Detour delay

Detour delay is the additional distance travelled to detour around the work zone.

Some studies have provided a more nuanced categorization of situations such as stopping and idling [30,115].

It is imperative to make informed estimations or assumptions about work zone parameters (such as work zone length, duration of lane closures, limited speed, etc.) and the road capacity, before calculating additional user GHG emissions from this procedure, as

Table 4
Summaries of studies: calculation methods of GHG emission induced by traffic delays of work zone.

Input parameters for work zones	Impact on traffic flow	Calculation method	Calculation type	Source
• Hourly traffic conditions • Speed limit and time • Free-flow capacity • Queue dissipation capacity • Work zone length • Capacity	Evaluated by RealCost tool: • Queue times and speeds • Number of vehicles affected	CO_2 emissions as a function of vehicle speed and pavement IRI	Equation	[51]
• Work zone length • Limited speed • Lane closures conditions	—	Extra CO_2 emissions associated with each unit of deceleration and speed change for a single vehicle	Equation	[116]
• Lane closures conditions	Simulated by VISSIM software • Speed and acceleration of vehicles affected by work zone activities	CMEM models	Model	[117]
• Work zone length • Speed limit • Lane closure conditions	—	MOVES	Model	[119]
• Lane closure conditions	—	A calculation tool developed by the Flemish Agency for Roads and Traffic	Table Tool	[118]
• Traffic volume • Work zone speed limit • Lane capacity • Detour distance • The number of lane closures.	Evaluated by RealCost tool: • Extra time to traverse the work zone	Extra vehicle kilometres travelled due to speed change delay	Equation	[48]
• Work zone length • Speed limit • Road capacity • Queue dissipation capacity • Maximum queue length	Modelled by using HCM 2000: • Changes in driving patterns	COPERTv5.0	Model	[76]
• Traffic conditions • Road capacity • Road conditions • Fuel consumption • GHG emission parameters	—	Rough emission equations for four types of traffic delays	Equation	[30]

shown in Fig. 6. This is often derived from experience or relevant construction documents. As summarized in Table 4, Chen et al. [51] used the RealCost tool developed by the FHWA to evaluate the impact of work zones on traffic delays: parameters based on the New Jersey Road User Cost Manual as inputs, and outputs that include queue times, queue speeds, and number of vehicles affected, are then used in a CO_2 emission function. Liu et al. [116] estimated data on work zone characteristics based on documents such as engineering files, field investigations and relevant standards. In a case study, two maintenance activity lane closure conditions and traffic flow diversions were assumed. Liu et al. [117] modelled three-lane closure and traffic flow diversion scenarios for two-lane road construction using the VISSIM software, which simulated affected traffic patterns and provided outputs on vehicle speeds and accelerations.

After establishing work zone scenario assumptions, GHG emissions from vehicles affected by traffic delays are calculated based on work zone parameters and traffic flow data from the affected road. The subject of GHG emissions is vehicles, so many studies have also combined it with vehicle emissions models. For example, Liu et al. [30] used the MOVES model to obtain region-specific emission factors for hauling and traffic delays during construction. Liu et al. [116] modelled vehicle emissions for light-duty vehicles (LDVs) and heavy-duty vehicles (HDVs) to determine the extra CO_2 emissions per unit of deceleration-related and per unit of speed change-related emissions of a single vehicle. In another study, Liu et al. [117] used the output of VISSIM to link with the CMEM model based on the work zone setting to generate the vehicle's second-by-second CO_2 emissions. Chong and Wang [48] introduced the concept of extra vehicle kilometres travelled, which translates the impact of each type of traffic delay into an equivalent number of extra vehicle kilometres travelled. Besides, incorporating the pavement construction cycle, the Flemish Agency for Roads and Traffic developed a calculation tool compiled from Excel that is related to a specific construction scenario and looks like a schedule with 1-h intervals. Every time slot has a corresponding CO_2 emission value, depending on the chosen scenario, the day of the week and the hour of the day [118].

2.2.6. End of Life Phase

At the EOL phase of pavement, the environmental impacts depend on the final disposition, either remaining in place as a base for a new pavement structure or being removed. When the pavement is removed, milled and crushed pavement materials can substitute for the virgin aggregate of sub-base/bases, or the virgin asphalt and aggregate in a new HMA. As for concrete pavement, whether landfilled or recycled, crushed pavement materials can continue to maximize their carbon uptake potential due to the specific surface area increase. GHG emissions from energy consumption from machines operation during pavement removal work during the EOL phase can be calculated in the same way as in the construction or M&R phase, and carbon uptake is the same. Exploring the allocation of GHG emissions from the EOL phase and environmental benefits from recycled materials and carbon uptake is crucial for clarifying the responsibility of pavements in carbon trading [120].

Table. 5 summarizes the allocation methods of environmental benefit and burden in the EOL phase in existing studies. Depending on the allocation of the environmental benefits of recycled materials between original and future systems after the EOL phase, common methods used in existing studies include cut-off, substitution and 50/50 methods. Additionally, the closed-loop and mass-loss methods are also utilized [121–123]. The cut-off method allocates environmental burdens solely to the product they directly associate with, without assuming the recoverability of the current pavement system at the EOL phase, and all environmental benefits are attributed to the pavement recycling system [124]. It is usually applied in the LCA of open recycling systems and is currently the most widely used method, due to the difficulty in predicting the future reuse of recycled materials and accurately quantifying recycling rates [125–127]. Both Piao et al. [128] and Aurangzeb et al. [129] did not consider the environmental burden of RAP in their source pavements from the EOL phase in the life-cycle assessment of pavements using RAP materials. Chong and Wang [48] use a cut-off method for the EOL phase, considering that the existing pavement would not receive any environmental benefits due to its potential to produce reclaimed material and apply transportation, construction, and M&R modules to calculate GHG emissions due to demolition and transportation of materials in the EOL phase. Lastra-González et al. [130] also applied the same cut-off method in evaluating the performance of asphalt mixtures using plastic waste to replace 25 % of the virgin bitumen, assuming that the environmental burdens from the RAP obtained by milling the pavement were contained within the system boundary while giving no credit for them.

The substitution method considers all recycling burdens to be associated with systems that use recycled materials to replace virgin materials. Huang et al. [131] conducted a sensitivity analysis of different methods for considering the EOL phase of pavement LCA and concluded that the cut-off method and substitution method are the two poles of the EOL allocation. Typically, this method is applied to certain metals that retain their intrinsic properties when recycled [124]. However, unlike the metals mentioned above, most pavement materials do not retain the same inherent properties when recycled, making substitution methods often not applicable [132].

The 50/50 method presents the basic principle that both supply and demand are necessary to achieve recycling. Therefore, half of

Table 5
Summaries of studies: allocation methods of environmental benefit and burden in the EOL phase.

Allocation method	Recycled material type	Source
Cut-off	—	[48]
	Reclaimed asphalt pavement	[128]
	Plastic waste	[130]
	Reclaimed asphalt pavement	[129]
	Reclaimed asphalt pavement	[137]
50/50	Plastic, rubber	[133]
	—	[134]

the environmental benefits of recycling are allocated to new pavement systems that use recycled materials, while the other half is allocated to systems that produce recyclable materials [121]. According to the impact formula, the use of recycled materials and the production of recyclable products are preferred when the environmental impact of recycling is less than the combined impact of the production of virgin materials and final waste disposal. The LCA model constructed by Yu et al. [133] employs a 50/50 method to give equal benefits to upstream producers and downstream users. The asphalt Pavement Embodied Carbon Tool (asPECT) follows the route of the 50/50 method but with a modified ratio of 60:40 [134]. Hasan et al. [135] discuss the impact of recycled RAP allocation methods: in comparison, the difference in environmental emission reductions between the "100:0" and "50:50" allocations ranged from 0.13 % to 7.44 %.

The closed-loop method assumes that each product is equally responsible for the environmental impacts associated with the production of virgin materials, recycling and final waste disposal. Impacts are therefore equally distributed among products in the life-cycle according to the number of times they are recycled, and it is suitable for use when the loss of weight of the recycled material is not significant [136]. Similarly, the quality loss method distributes impacts based on their value over the product's life-cycle (weighting factor), based on the principle that the material suffers a loss in quality which necessitates a certain level of upgrading to restore its function. However, the closed-loop method and quality loss method require knowledge of the fate of the material, which is often beyond the analysis cycle of pavement LCA and therefore rarely used in existing studies [131].

Changes in allocation methods can add complexity to LCA results. Therefore, pavement materials and by-products should be appropriately allocated according to rules appropriate to the processes and fate of the materials involved, ideally as described in the Product Category Rules (PCR) [138]. Besides, in various national standards, pavements are assigned design lives, after which they are expected to undergo structural evaluation and maintenance. However, in practical scenarios, there is controversy over when, or if, pavements will "die". Reaching the design life often does not indicate the end of life of the pavement, as frequent maintenance and rehabilitation can restore the functionality, resulting in few pavements reaching a true end of life state or achieving their intended service life [46,48,76]. Unlike other infrastructures in the building sector, pavements have a unique concept of EOL, viewed as a long-term process rather than an abrupt event. The material removed during maintenance symbolizes a partial "death" of pavements. Consequently, accurately assessing the environmental benefits generated by the EOL of pavements requires considering both the original materials and maintenance activities over the long-use phase.

3. Discussion

3.1. Pavement LCA tools

Since the application of LCA to the field of road infrastructure, numerous mature and practicable platforms or tools have been developed for carbon footprint or other environmental impact assessments. They target various audiences, covering all phases of the pavement life-cycle and addressing diverse environmental impacts. Characteristically, they offer varying degrees of accuracy within defined functional units and system boundaries [139,140].

Besides, they also have different levels of user interaction and interpretability: some allow only default processes and data to be used, while others allow users to use their data and select parameters or datasets from appropriate databases or other sources according to the characteristics of the case. Therefore, they vary in their scope of application (global, national or regional, etc.), and estimation accuracy. As shown in Table 6, this study reviews the widely used existing pavement LCA tools and compares them at the various phases of the full pavement life-cycle of concern, functions and features. It is important to mention that the environmental impacts of the LCA of concern in this study only include GHG emissions. Moreover, some mature commercial tools and software are applicable in various fields such as SimaPro, Gabi, etc. Their application in the pavement field cannot be directly categorised into certain phases and therefore will not be discussed here.

3.2. Uncertainties in pavement LCA

While the application of LCA has become gradually more widespread, a serious criticism is the effect of uncertainties in LCA on the reliability and interpretability of results [141]. As an example, in the study of Liu et al.[142] the uncertainty contributions of lime and SBS-modified asphalt can reach 32.8 % and 54.6 % at the material phase. LCA outputs are typically presented as point estimates without accompanying confidence intervals or associated margins of error, due to methodological ambiguity in accounting for uncertainty, whether epistemic or aleatory [143]. Huijbregts [144] developed a framework to categorize uncertainties in LCA: data uncertainty, model uncertainty and uncertainty due to the choice. As reflected in pavement LCA, the source of data uncertainty is the long life-cycle and interactions with multiple parties such as the environment, users and contractors, which leads to data errors, data unrepresentativeness, and even missing data [145]. The source of model uncertainties is the range of external variations that may affect the model input parameters; in the case of emission factors. Examples of choices leading to uncertainties in the inventory analysis are the choice of the functional unit and the choice of the allocation procedure for multi-output processes, multi-waste processes and open-loop recycling [144,146].

Despite numerous studies and standards to date that have clarified the importance of uncertainty, there is still a lack of specific, detailed and operationally standardized assessment methods, which has led to many studies failing to consider the impact of uncertainty in the results of GHG emissions calculations on conclusions or decision-making. Some previous relevant studies applied a one-factor-at-a-time sensitivity analysis, but this may be inefficient when considering the combined effects of different uncertainties affecting various parameters [147]. To cope with this problem, some scholars have researched the quantification of LCA uncertainty at

Table 6
Pavement LCA tools.

Tools	Developer	Life-cycle phases						Functions	Features
		Material Production	Transportation	Construction Activities	PVI	Traffic Delay	EOL		
CHANGER	International Road Federation (IRF)	√	√	√	-	-	√	Estimating the carbon footprint of road construction activitiesPromoting environmental analysis;Providing a basis for comparative analysis and optimization of options.	Adopting a **process-based** modeling approach with equations to estimate GHG emissions from each identified and quantified source.
PaLATE	Department of Environmental and Civil Engineering at the University of California	√	√	√	-	-	√	Assessing the environmental and economic effects, and sustainability of road construction and maintenance.	The **Excel-based** tool is flexible and transparent, allowing sensitivity analysis with varying construction and maintenance schedules and discount rates.
asPECT	UK Transport Research Laboratory	√	√	√	-	-	√	Informing material decisions for asphalt pavements	Requiring more **diverse data inputs**, enhancing result reliability through accuracy, but also increasing complexity compared to similar tools.
ROAD-RES	The Technical University of Denmark	√	√	√	-	-	√	Evaluating the environmental impacts and resource consumption in different phases of road construction with virgin materials and residues from waste incineration;Evaluating and comparing two disposal options of waste incineration residues: landfill and road use.	ROAD-RES can assess complex long-term leaching of residues and other environmental impacts.
CO_2NSTRUCT	funded by the European Union's Horizon Europe research and innovation programme	√	√	√	-	-	-	An EU-funded project to identify, test and quantify the impacts of the circular economy in climate mitigation models.	Enhancing climate models with **circular** economy measures, improving their ability to assess circular options and addressing the limitations of linear models in capturing value chain feedback loops.
Athena Pavement LCA	the Cement Association of Canada and Athena Institute members	√	√	√	-	-	-	Providing environmental LCA results for material manufacturing, road construction, and maintenance. Supporting custom road designs, enabling quick comparison of multiple options across varying road lifespans.	PVI effects can be estimated by inputting road roughness and deflection modulus values, helping users understand trade-offs.
MOVES	The U.S Environment Protection Agency (EPA)	-	-	-	-	-	-	Estimating criteria air pollutants, greenhouse gases, and air toxics from mobile sources at national, county, and project levels;Creating emission factors or inventories for on-road vehicles and off-road equipment.	Although MOVES are not direct emissions from pavement projects, they contribute to the usage phase and traffic delays.

different phases of the road life-cycle, mainly for model uncertainty, including [142]: 1) Interval methods, for example, Bhat and Mukherjee [148] developed a method based on the first-order approximation of Taylor, which propagates parameter uncertainty through the LCA results and identifies the equivalent intervals that can be applied in the material procurement decision-making process; 2) and probabilistic methods, where the propagation and quantification of uncertainty is presented as a probability distribution, as shown in Fig. 7. Cao et al. [149] performed an LCA on the WMA of rubber and estimated the basic and additional uncertainties. The basic uncertainty can be ideally modeled with a probability distribution and incorporated into the LCA framework through a Monte Carlo simulation approach that quantifies and propagates four uncertainty categories: material energy consumption, equipment energy consumption, mixing temperature reduction, and material transportation distance. For additional uncertainties, data quality indicators (DQIs) were quantified using the spectral matrix approach developed by Weidema and Wesnaes [150] and incorporated into a lognormal distribution derived from the aforementioned basic uncertainties. Yu et al. [145] analyzed CO_2 emissions during asphalt pavement maintenance and established a statistical methodology for assessing uncertainty in energy consumption and CO_2 emissions, identifying two sources of uncertainty, data quality uncertainty, which is captured by transforming the input data into a probability density function (PDF) using a Beta distribution according to the definition of the data quality spectral matrix, and model parameter uncertainty, which is evaluated by defining the Uncertainty Factor (UF) to determine the form and parameters of the distribution. Beyond this, Yoo et al. [151] argue that the above traditional approaches rarely focus on the aggregated results of the maintenance and construction phase of a pavement project and rarely assess the uncertainty in environmental emissions, and therefore develop a new system-level method to reduce the additional uncertainty: proposing to implement a consistent weighting process to derive a system-level Aggregate Data Quality Indicator (ADQI), based on which a modified beta distribution can be obtained.

Uncertainty, especially from data quality, is actually difficult to overcome completely, so it is even more important to integrate the quantification of uncertainty into the undertaking of the LCA and to report the results in a probabilistic manner to assess the GHG emissions of the pavement under uncertainty, which also provides a reasonable prerequisite for the comparability of LCA.

4. Conclusions

This study aims to analyze calculation methods and LCA characteristics of existing pavement GHG emission studies in the scientific literature and provide a critical overview of their accuracy, availability, uncertainty and applicability, and discuss the advancement of LCA models across different phases worldwide. It provides references and recommendations for studies with different objectives and scenarios and creates the basis for future homogenization of pavement LCA.

- Calculation methods and pavement LCA in existing studies often have 1) different research objectives, for example as a tool for calculating GHG emissions from pavement projects, as a reference for comparison of different technologies, and construction/maintenance programs and as a criterion for environmental benefits in activities such as tendering; 2) different phases included, such as at the design or feasibility assessment phase where construction has not yet taken place, cradle-to-gate or cradle-to-grave, where the pavement project has already been put into service; 3) different levels of assessment, including calculations for individual pavement projects and for regional or national road networks. These has predominantly led to the development of methods or tools with limited universality, giving rise to non-comparable calculation results.
- The more phases that are covered in the calculation of GHG emissions from pavements over the entire life cycle of a road, the more stakeholders are involved, and there are trade-offs in emissions between decisions made at different phases. Meanwhile, most of the current studies and tools developed at the project level focus on the comparison and estimation of material choices or construction alternatives. These limit the ability to select more integrated and emission-reducing strategies at the full life-cycle, road network-level, or region-level. In future research, roads need to be considered as a complex system, and network-level and region-level assessment tools can be developed to guide decision-making over the full life-cycle.
- Existing studies on PVI is more often applied to pavement performance assessment and maintenance decisions, mostly using simple linear descriptions of a single factor, and the resulting user emissions are not attributed to the life cycle of the road sector in terms of responsibility. Therefore, in the development of future project-level road assessment tools, on the one hand, extra user emissions need to be taken into account in the road sector by applying traffic flow and pavement performance data during road operation phase; on the other hand since the three factors have different significance of impacts on different types of pavements in different environments (e.g., roughness-induced PVI is important for roads with high passenger car traffic, whereas deflection-induced PVI is important for local roads and state highways with high truck traffic), a single-factor approach (e.g., considering only IRI) can produce biases in the results, which can lead to incomparable results, and thus the development of calculation models needs to take all three factors into account fully, even if some of the accuracy is discarded.
- Uncertainty in the LCA of GHG emissions from pavements arises from data uncertainty, modeling uncertainty, and choice-induced uncertainty. The results of many relevant studies are currently presented as point estimates without accompanying confidence intervals or associated error margins, and lack of uncertainty quantification, which affects the credibility of the results. Future research suggests incorporating quantification of uncertainty into LCA and reporting the results in a probabilistic manner, which is not only for the purpose of comparing the reliability of assessment results, but also for the purpose of setting pavement standards in future carbon trading.

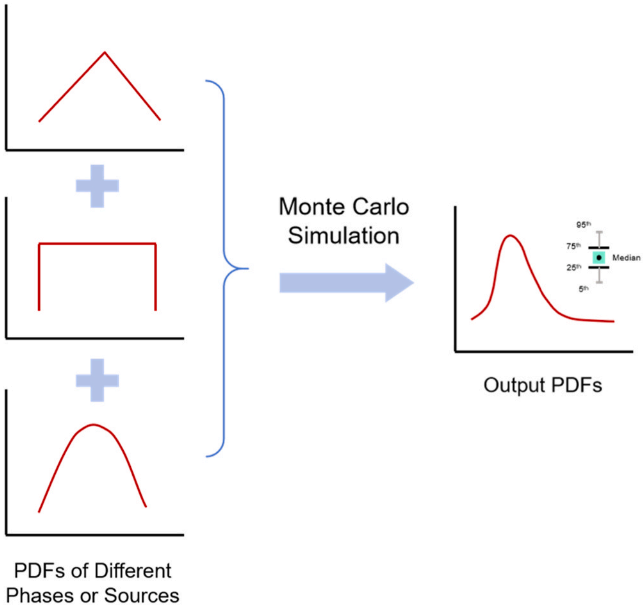

Fig. 7. Schematic plot of uncertainty propagation process [145].

CRediT authorship contribution statement

Yuchuan Du: Methodology, Funding acquisition, Conceptualization. **Ziyue Gao:** Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Conceptualization. **Chenglong Liu:** Writing – review & editing, Methodology, Funding acquisition, Conceptualization. **Zihang Weng:** Writing – review & editing, Conceptualization. **Xiangyu Ren:** Visualization. **Wenxiang Li:** Writing – review & editing.

Declaration of Competing Interest

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

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Data availability

No data was used for the research described in the article.

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