Including maintenance in life cycle assessment of road and rail infrastructure—a literature review

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Abstract

Purpose LCA is increasingly used in infrastructure policy and planning. This study maps approaches used in comparative LCA of road and rail infrastructure to (1) determine the length of the analysis period, (2) estimate the maintenance frequency, and (3) include the effects of climate change on infrastructure performance. A LCA may need to fulfil different requirements in different decision-contexts. The relevance of the approaches for decision-making in policy and procurement is therefore discussed.

Methods Ninety-two comparative LCAs of road and rail infrastructure published in peer-reviewed journals January 2016–July 2020 were reviewed. Papers were found through a systematic process of searching electronic databases, applying inclusion criteria, and conducting backward and forward snowballing.

Results and discussion The analysis period was commonly determined based on infrastructure service life. The maintenance frequency was estimated based on current practice, laboratory tests, modelling, or scenarios. The effects of climate change were considered in two papers by comparing results in a control case and in a changed climate. In policy and procurement, current practice approaches are not adapted to innovative solutions or to climate change. Modelling and laboratory tests could improve calculations of the maintenance phase but might have some limitations related to innovative solutions. Scenarios could be readily applied in a policy context; however, in procurement, consistent and generic scenarios should be used.

Conclusions Results suggest what approaches could be used to account for maintenance in infrastructure LCA depending on the decision-context. The LCA community is suggested to research other approaches than current practice to account for long analysis periods, climate change, and innovative solutions. Additionally, literature not covered here could be reviewed for additional approaches and perspectives. Examples include stand-alone LCAs, method development papers, papers on the individual approaches and decision-contexts, certification systems, standards, and guidelines.

Keywords Life cycle assessment · Infrastructure · Road · Rail · Maintenance · Review · Procurement · Policy

1 Introduction

Since the 1990s, life cycle assessment (LCA) has been conducted to assess the environmental impacts of road and rail infrastructure (Santero et al. 2011a; Olugbenga et al. 2019). The LCAs cover a variety of infrastructure forms, including surface roads, tunnels, and bridges as well as ancillary components such as crash barriers. Many of the infrastructure LCAs aim to compare different construction solutions or construction materials to determine which alternative has the lowest environmental impacts from a life cycle perspective.

More recently, LCA has become increasingly used as strategic decision-support within infrastructure policy and planning, for example in procurement (Saxe and Kasraian 2020). As decision-support, LCA can be conducted at different

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decision-levels: the network level and the project level. At the project level, a LCA is conducted for a single construction project, whereas a LCA at the network level is conducted for several construction projects (Butt et al. 2015). LCA can be used throughout the planning of infrastructure projects, from early planning (such as choice of road location) to late planning (such as choice of design) (ibid.). The implementation of LCA in procurement is an example of a project level LCA conducted in late planning (Butt et al. 2015). In practice, several countries have implemented, or plan to implement, LCA in infrastructure procurement. Examples include Sweden (Toller and Larsson 2017), Canada (Future Cities Canada 2018), The Netherlands (Keijzer et al. 2015), and Belgium (Anthonissen et al. 2016).

In a LCA, the life cycle of infrastructure is commonly divided into five stages: material production, construction, maintenance, operation, and end-of-life. This study focuses on the maintenance stage. An infrastructure project has a long service life and, to maintain its functionality, it requires maintenance for many years to come. The maintenance activities contribute to the total life cycle impacts of a project. Liljenström et al. (2019) found that maintenance (including reinvestment) of Swedish infrastructure contributes more to the annual climate impact than new construction, showing that impacts from infrastructure maintenance must also be reduced.

The environmental impacts of maintenance could be affected in the design stage by designing infrastructure with low maintenance related impacts. For example, LCAs comparing construction solutions have found that the material with highest production related impacts might have lower life cycle impacts due to reduced maintenance needs and longer service life (see for example Penadés-Plà et al. (2017)). However, the assessment of maintenance related impacts in LCA is uncertain due to data uncertainty, methodological uncertainty, and uncertainty about the future performance.

One uncertain aspect in infrastructure LCA, which influences the quantified impacts of maintenance, is the length of the analysis period. The analysis period corresponds to “the time period over which the functional unit is evaluated” (Santero et al. 2011b), i.e. for how many years into the future that maintenance activities are considered. There is no standardised way to select analysis period in infrastructure LCA. Although the analysis period could be based on the infrastructure service life, infrastructure is long-lived without a well-defined end-of-life, and hence, the service life can be difficult to determine (Saxe and Kasraian 2020).

Another uncertain aspect that influences the quantified impacts of maintenance is the maintenance frequency, i.e. how often maintenance is conducted during the analysis period. Estimating the maintenance frequency is difficult because of the uncertainties involved in predicting the many

factors that influence infrastructure performance, for example climate, material characteristics, and future traffic. The topic of maintenance frequency has gained some attention in the field of infrastructure LCA. Several studies have concluded that the maintenance stage is often calculated without accounting for realistic maintenance schedules (Santero et al. 2011a; AzariJafari et al. 2016; Hamdar et al. 2016; Inyim et al. 2016; Jiang and Wu 2019).

Yet another uncertain aspect of importance in infrastructure LCA is the change in external factors, such as the biosphere, that could influence future maintenance needs. Due to the commonly long analysis periods used in infrastructure LCA such changes are likely to occur during the analysis period. Future climate change is predicted to affect the infrastructure’s structural performance, and thereby its maintenance frequency, due to, for instance, changes in temperature, precipitation, and frequency of extreme weather events (Arent et al. 2014).

Previous literature reviews have noted that limitations in the calculation of maintenance related impacts hinder the utility (Santero et al. 2011a) and implementation (Jiang and Wu, 2019) of road LCAs, as well as the ability to determine which road surface material that has the lowest environmental impacts (Santero et al. 2011a; Inyim et al. 2016). However, these reviews do not describe the methodological approaches used in the reviewed LCAs or the reasons why a particular approach was chosen. Depending on the decision-context, for example a procurement or a policy decision, there are different requirements on a LCA (Butt et al. 2015). Hence, the appropriate approach to consider future maintenance in LCA will likely depend on the decision-context. As LCA is used more frequently in infrastructure policy and procurement, the choice of methodological approach becomes of increased importance.

This study aims to conduct a systematic literature review to map and describe approaches used in LCA of road and rail infrastructure. The study maps approaches used to (1) determine the length of the analysis period, (2) estimate the maintenance frequency, and (3) include the effects of future climate change on the service life and the maintenance frequency. The relevance of the approaches for decision-making is then covered from two perspectives: (1) based on characteristics of the construction solutions analysed and (2) based on characteristics of specific decision-contexts.

2 Method

The papers included in the literature review were found through a systematic process of searching electronic databases, applying inclusion criteria, and conducting backward and forward snowballing. The papers were analysed to find approaches used to (1) determine the length of the analysis

period, (2) estimate the maintenance frequency, and (3) include the effects of future climate change on service life and maintenance frequency.

2.1 Inclusion criteria

Eight inclusion criteria were applied to the papers identified in the database search. Papers were included that:

1. Apply environmental LCA
2. Are about road or rail infrastructure
3. Account for future infrastructure maintenance
4. Are written in English
5. Are published in peer-reviewed scientific journals
6. Are published January 2016–July 2020
7. Perform a comparative LCA
8. Perform a project level LCA

The term maintenance can cover several activities, such as regular maintenance, repairs, and rehabilitations. In the review, LCAs that account for an activity that could be classified as maintenance (i.e. an activity conducted after construction but before end-of-life with the aim to maintain or restore the infrastructure's function) were included.

The review was limited to papers published January 2016–July 2020 covering a large body of publications. Although the limited search period risks excluding relevant publications, it can be assumed that important methodologies used in earlier research are also used in the publications included.

The review was also limited to comparative LCAs covering comparisons of construction materials, construction technologies, road locations, design alternatives, and maintenance strategies. The methodological issues considered in this study (analysis period, maintenance frequency, and climate change effects) are more important in comparative LCAs than in stand-alone LCAs. In comparative LCAs, the compared alternatives can have different characteristics and the approach used to calculate maintenance related impacts might therefore affect the outcome of the study.

Additionally, the review focused on studies at the project level; network level studies were not included. This delimitation was made since the review focuses on future maintenance of new construction projects.

2.2 Databases and snowballing

Three databases were used in the literature search: Scopus, Web of Science, and GreenFile. Scopus and Web of Science were chosen for their large coverage of literature within the fields of natural science and engineering. GreenFile was chosen because of its specific focus on topics related to environmental impacts.

The databases were searched on 31 March 2020. After duplicates had been removed and the inclusion criteria had been applied, backward snowballing (searching through the reference list of the selected papers) and forward snowballing (searching for papers referring to the selected papers) were used to find additional papers that fulfilled the inclusion criteria. Finally, the three databases were searched again on 20 July 2020 to find papers that had been published since the search in March.

2.3 Search criteria and search string

The first step of the literature review was a broad database search aiming to find papers that include LCA of road and rail infrastructure. The first search criterion was that the paper includes a LCA. The second search criterion was that the paper covers road or rail infrastructure. Since the term maintenance (and its synonyms) is not necessarily used in titles, abstracts, or keywords of infrastructure LCAs (even when included in the scope) it was not included in the search string. Exclusion search terms were not added. The same search string was used in all three databases. Based on the search criteria, the following search string was used to search within article titles, abstracts, and keywords:

("life cycle assessment" OR LCA OR "life cycle analysis") AND (road* OR rail* OR pavement* OR bridge* OR tunnel*).

2.4 Paper selection

The papers were selected through a stepwise procedure outlined in Fig. 1.

First, 3859 papers were identified in the initial database searches in March 2020. When duplicates, conference papers, books, and book chapters had been removed, the remaining papers were screened in multiple stages: first based on the title, then based on the abstracts, and finally based on the full text. The full texts of 14 papers were not found.

Second, the scope of the review was focused on comparative LCAs published January 2016–July 2020 and additional papers were removed. The remaining papers were screened to find comparative LCAs on a project level and to remove network level LCAs and stand-alone LCAs. The database search in July was made following the same procedure as the search in March.

Third, for the resulting list of papers, backward and forward snowballing were conducted until no more studies were found. During snowballing (both backwards and forwards), only papers published January 2016–July 2020 were screened (using the same procedure as for the database searches).

In the end, 92 papers were selected for the review.

Fig. 1 Process for literature search

2.5 Data collection process

The analysis focused on finding the papers' arguments (including the references supporting these arguments) for determining analysis period, estimating maintenance frequency, and considering effects of future climate change. The arguments were categorised into different approaches (see Sect. 3) based on common characteristics identified by the authors of this review. If a paper supported an argument by referring to another study, the paper was categorised according to the approach used in the original reference.

Papers comparing innovative and conventional construction solutions are described in Sect. 3.5.2. In this review, innovative construction solutions are defined as solutions that are not yet used in practice, solutions that have been used for a short time, and solutions that have been available for some time but are not commonly used. Papers that described the construction solutions as innovative, emerging, new, or a contrast to conventional solutions were considered to include innovative solutions.

3 Results

3.1 Description of the studies included in the review

Table 4 (in the Appendix) presents the scope of the reviewed papers, including the forms of infrastructure covered and the construction alternatives compared.

Out of the 92 papers included, 84 papers were about road infrastructure (whereof 1 was for pedestrian traffic) and 7 about rail infrastructure (Table 4 in the Appendix). One paper analysed a component that can be applied in both road and rail infrastructure.

Different types of road and rail infrastructure were covered in the reviewed literature (Table 4 in the Appendix). Most of the road LCAs were about surface roads (53 papers) and bridges (22 papers). Other forms of infrastructure were less common: tunnels (3 papers), roundabouts (1 paper), crash barriers (1 paper), anti-glare devices (1 paper), culverts (1 paper), and road drainage (1 paper). One paper included three forms of infrastructure: bridge, tunnel, and surface road. The rail infrastructure LCAs covered track beds (3 papers), bridges (2 papers), noise and vibration mitigation measures (1 paper), and sleepers (1 paper).

The papers compared a variety of construction materials, construction technologies, road locations, design alternatives, and maintenance strategies (Table 4 in the Appendix). Most of the papers compared different construction materials. For example, 38 of the road LCAs compared different types of road surface materials. Additionally, a common aim (in about 50% of the papers) was to compare a conventional construction solution with an innovative construction solution (Table 4 in the Appendix).

3.2 Approaches used to determine the length of the analysis period

The analysis period, which determines for how many years into the future the maintenance stage is accounted for, has a significant influence on the LCA results. The analysis period should not be confused with the infrastructure service life, which is the intended life length of the infrastructure. Although the analysis period can be equal to the service life, it does not have to be. A service life can be specified for the complete project (for example the service life of a bridge) and for each individual component of the infrastructure (for example the road surface on the bridge). The latter case is related to the maintenance frequency since infrastructure is designed for a specific service life, assuming regular maintenance when needed.

Based on the publications in this review, nine approaches to determine the analysis period were identified

Table 1 Approaches used to determine length of the analysis period and share of papers applying each approach based on how the papers were categorised in this review

Approach to determine analysis period	Share of papers applying the approach ¹
Design service life	30%
Estimated by experts	2%
Predicted performance	2%
Period of use	2%
Service life of adjacent infrastructure	1%
Fixed analysis period	7%
Fixed number of maintenance cycles	4%
Combination of approaches	4%
No motivation	54%

¹The total does not equal 100% since some papers use multiple approaches

(Table 1). A large share of the papers (54%) provided no motivation for choice of approach (either no argument was made, the references used could not be accessed, or the original reference did not support the arguments made). Some papers (4%) used a combination of the approaches listed in Table 1 to find an analysis period fitting the scope of the study. The other seven approaches were divided into two main categories: (1) approaches based on the service life and (2) approaches based on a fixed analysis period or a fixed number of maintenance cycles.

3.2.1 Service life

In 37% of the papers, the analysis period was determined based on the infrastructure service life (Table 5 in the Appendix). However, the service life was defined in various ways. Often (in 30% of the papers), the service life was the same as the design service life, i.e. the intended life length of the infrastructure. The design service life was estimated using several different sources, including regional or European guidelines for infrastructure design, design information, and the desired service life for a specific construction project. In other cases (2%), the service life was estimated by experts (such as manufacturers or others with knowledge about the construction sector) or based on predicted performance (2%) by using modelling or laboratory tests. In a couple of papers (2%), the service life explicitly represented the actual period of use, which may be significantly different from the design service life. In one case (1%), the analysis period equalled the service life of adjacent infrastructure (sewer pipes) with the motivation that the road must be rebuilt when replacing the sewer pipes under the road.

3.2.2 Fixed analysis period or number of maintenance cycles

In some papers (11%), the analysis period had no direct connection to the service life of a specific construction project. In these papers (Table 5 in the Appendix), the analysis period sometimes represented fixed temporal boundaries (7%), i.e. a fixed analysis period, that were specified in guidelines for assessment methods such as LCA (through Product Category Rules), life cycle cost analysis (LCCA), or cost–benefit analysis. In a few other papers (4%), the analysis period was instead chosen to cover a fixed number of maintenance cycles for each alternative.

3.3 Approaches used to estimate the maintenance frequency

The maintenance frequency specifies how often maintenance is conducted during the analysis period and it could therefore have a significant influence on the results of a LCA.

The following approaches to estimate maintenance frequency were found in the reviewed papers: current practice (37%), laboratory tests (4%), modelling (37%), and scenarios (8%) (Table 2). Some papers used a combination of approaches; however, in this review, each approach is described individually. For 25% of the papers, it could not be determined how the maintenance frequency was estimated (either no motivation was provided, the references used could not be accessed, or the original reference did not support the arguments made).

3.3.1 Current practice

In 37% of the papers, the maintenance frequency was estimated based on current practice of infrastructure maintenance (Table 6 in the Appendix). Even though these papers shared a principally similar approach, “current practice” was determined in a variety of ways. The most common

way (applied in more than half of the papers using a current practice approach) was a reference to a maintenance plan currently used by a transport agency, to construction guidelines, or to national standards and regulations. Current practice was also estimated by experts (such as manufacturers, construction companies, and designers) through for example interviews, surveys, statistics, and field observations.

3.3.2 Laboratory tests

In 4% of the papers, the maintenance frequency was estimated based on laboratory tests (Table 6 in the Appendix) in which a surface material was tested in a laboratory to determine its durability.

Two papers using laboratory tests conducted fatigue testing of asphalt mixtures. The tests were based on laboratory prepared specimens as well as cores from full-scale application in a trial section or in a testing facility. In another paper, the method used could not be traced from the original sources. In all three cases, material durability was evaluated relative to another material. In the fourth paper, no physical sample was analysed; rather, embedded sensors registering the material condition was applied to a road surface in a testing facility.

In the paper using full-scale application at a testing facility, the approach was motivated by the importance of determining a mixture’s field performance and the limitations associated with current practice approaches and tests on laboratory prepared specimens: they cannot be used to predict actual maintenance demand and actual behaviour of asphalt mixtures (Saeedzadeh et al. 2018).

3.3.3 Modelling

Modelling was used in 37% of the studies to estimate the maintenance frequency (Table 6 in the Appendix). This approach is characterised by the use of models that predict the future infrastructure condition (and thereby when maintenance is needed) based on the infrastructure’s present state and future scenarios related to parameters affecting maintenance needs. The reason for estimating maintenance frequency based on modelling was rarely stated explicitly. However, in one case, modelling was chosen due to limitations with laboratory tests: there is no correlation between laboratory results and material durability in practice (Rodríguez-Fernández et al. 2020).

In the reviewed papers, modelling was used for a variety of infrastructure types, including different types of road surface materials, concrete bridges, ballast layers, and crash barriers. Several types of models based on different underlying principles were used. In all bridge LCAs that applied modelling, diffusion of chloride ions in the concrete was modelled. Among the road LCAs, both empirical,

Table 2 Approaches used to estimate maintenance frequency and share of papers applying each approach based on how papers were categorised in this review

Approach to estimate maintenance frequency	Share of papers applying the approach ¹
Current practice	37%
Laboratory tests	4%
Modelling	37%
Scenarios	8%
Not possible to determine	25%

¹The total does not equal 100% since some papers use multiple approaches

mechanistic-empirical (ME), and probabilistic models were used. Additionally, the papers included several expressions of road surface performance, such as cracking, rutting, roughness, “pavement condition index”, and “present serviceability index”.

Three of the papers using modelling aimed to compare different performance measures or different performance-prediction models. They showed that choice of performance measure affect ranking of alternatives (Hamdar et al. 2020) and lead to different estimated service lives (Hong and Prozzi 2018). They also noted that, although different performance-prediction models lead to different absolute results, the relative difference between materials is the same regardless of the model used (Rodríguez-Fernández et al. 2020).

3.3.4 Scenarios

In 8% of the papers, scenarios were used instead of a fixed maintenance frequency (Table 6 in the Appendix). These papers assumed that the maintenance frequency depends on some factor and several values for this factor were compared. In the papers, the maintenance frequency was assumed to depend on various factors including the maintenance budget (3 papers), the traffic load (1 paper), the maintenance practice (1 paper), and the material performance (2 papers).

3.4 Approaches used to include effects of future climate change

The analysis period in an infrastructure LCA is often long. About 70% of the papers reviewed applied an analysis period of 30 years or more (Table 5 in the Appendix). Consequently, most infrastructure projects analysed are expected to be used in 2050 or thereafter. During this analysis period, climate change might significantly influence the service life and maintenance frequency of infrastructure.

The majority of the papers reviewed did not consider climate change effects in the LCA (Table 3). Most papers (96%) did not mention the possible effect of climate change on the service life or the maintenance frequency. One paper (1%) acknowledged that such changes might happen and that including them could affect the results of the study, but the effect on environmental impacts was not quantified (Batouli et al. 2017). In one paper (1%), which included both a LCA and a LCCA, the effect of climate change on the maintenance frequency was considered in a sensitivity analysis for LCCA results (Cadenazzi et al. 2020).

In only two papers (2%), effects of climate change were considered when determining maintenance frequency in a LCA. Tuler and Kaewunruen (2017) compared alternative noise and vibration mitigation measures in a control case and in adverse climates; however, what is considered an adverse climate was unspecified. Setsobhonkul et al.

Table 3 Approaches used to consider the effects of climate change and share of papers applying each approach based on how papers were categorised in this review

Approach to consider climate change effects	Share of papers applying the approach
Not mentioned	96%
Quantified in sensitivity analysis for LCCA	1%
Mentioned, but not quantified	1%
Considered when determining maintenance frequency in LCA	2%

(2017) compared designs of transition zones between bridge and embankment in a control case and in case of hot/cold temperatures and floods. Neither of the papers considered regional climate change effects in a specific country. Rather, they specified, based on previous studies, how the service life and the maintenance frequency depended on general climate parameters, such as an adverse climate (Tuler and Kaewunruen 2017) or a hot climate (Setsobhonkul et al. 2017).

3.5 Use of approaches considering characteristics of the alternatives compared

Certain aspects in comparative LCA require that approaches to determine analysis period, estimate maintenance frequency, and include climate change effects are chosen carefully. This section illustrates how approaches were applied in comparative LCAs characterised by one of the following: (1) the alternatives have different service lives or (2) at least one of the alternatives is an innovative construction solution. This illustration provides further insight into the application of the approaches.

3.5.1 Comparing alternatives with different intended service lives

About 25% of the papers compared alternatives that have different intended service lives (Table 5 in the Appendix). When the alternatives have different service lives, the choice of approach to determine the analysis period poses a certain challenge because the alternatives must be compared fairly even though one has a longer service life than the other. In the papers reviewed, different ways to handle this situation were found.

A common approach in the papers was to compare the alternatives over a joint analysis period. The length of this joint analysis period was determined in different ways. The service life of each alternative was estimated using one of the approaches from Table 1. A joint analysis period was then chosen to correspond to the longest service life (e.g. Chen

et al. 2016; Noda et al. 2016; Huang et al. 2018; Rodríguez-Alloza et al. 2019; Cadenazzi et al. 2019, 2020; Landi et al. 2020), the shortest service life (Strippel et al. 2016; Cantisani et al. 2018), or a common denominator between the service lives (Liu et al. 2020). Others used an analysis period in which each alternative is rehabilitated at least once (Puccini et al. 2019) or that includes a complete life cycle of all alternatives (Batouli et al. 2017).

The papers applying a joint analysis period accounted for continuous replacement and maintenance of structures until the end of the analysis period. Papers that considered the end-of-life of alternatives also accounted for reconstruction of the alternative with the shortest service life (e.g. Noda et al. 2016; Strippel et al. 2016; Simões et al. 2017; Al-Ayish et al. 2018; Rodríguez-Alloza et al. 2019; Cadenazzi et al. 2019, 2020; Rempelos et al. 2020).

In a few other cases, no joint analysis period was determined. In these cases, various approaches listed in Table 1 were used to determine the service life of each alternative. One paper compared the alternatives using different service lives (Farina et al. 2017). In other papers (O’Born et al. 2016; Dolci et al. 2020), the results were annualised so that alternatives were compared over one year. Others used scenarios so that the alternatives were compared assuming different analysis periods (Krezo et al. 2016) or adjusted the functional unit so that the different service lives are reflected in the surface area constructed and maintained (Haslett et al. 2019).

3.5.2 At least one of the alternatives is an innovative construction solution

In about 50% of the reviewed papers, the aim was to compare the environmental impacts of conventional and innovative solutions (Table 4 in the Appendix). This situation poses specific challenges when determining maintenance frequency since the construction solution has not been used in practice and, consequently, only little information is available about its performance. Twelve of the papers analysing innovative construction solutions did not specify which approach was used to determine maintenance frequency. The other papers used one of the approaches identified in Sect. 3.3 to estimate the maintenance frequency of the innovative solutions.

A current practice approach was sometimes used (12 papers) for innovative construction solutions. In one paper, this choice was motivated by a lack of data for the innovative solution (Bizjak and Lenart 2018). In other cases (Bizjak et al. 2017; Santos et al. 2018a; Hasan et al. 2020), it was assumed that current practice was representative also for the innovative solution, for example because previous studies had shown that the performance of the innovative and conventional material was the same (Santos et al. 2018a; Hasan

et al. 2020). In several cases (Bizjak et al. 2017; Umer et al. 2017; Bizjak and Lenart 2018; Santos et al. 2018a, 2019; Hasan et al. 2020), the uncertainty introduced by using a current practice approach was acknowledged. Either, it was suggested that a sensitivity analysis be made in additional research (Hasan et al. 2020) or a sensitivity analysis (Bizjak et al. 2017; Bizjak and Lenart 2018; Santos et al. 2018a, 2019) or uncertainty analysis (Umer et al. 2017) was included. Two papers used expert estimations (Peñaloza et al. 2018; Iwase et al. 2020). In this review, expert estimations were considered a current practice approach (in 3.3.1); however, experts could consider special characteristics of the innovative materials in their assessments. In other cases, current practice approaches were used when a conventional technology was applied in a non-traditional setting (Cantisani et al. 2018) and when a technology had been available for some time but was less commonly used than other technologies (Liu et al. 2020).

Modelling was used to determine the maintenance frequency of innovative solutions in several papers (17 papers). These papers covered a variety of infrastructure forms and models. Generally, the papers did not describe the representativeness of the models for the innovative materials. However, Simões et al. (2017) noted that material degradation curves based on real data could not be predicted due to lack of case studies investigating material conditions in different situations. Thus, to conduct the study they had to use a standard degradation curve. In other cases, a sensitivity analysis was conducted to evaluate the model’s effect on the results (Chen et al. 2016; Bressi et al. 2018; Balieu et al. 2019).

In the majority of papers that used laboratory tests to determine maintenance frequency (3 papers) the aim was to assess the environmental impacts of an innovative solution. In all these papers (Lizasoain-Artega et al. 2019; Landi et al. 2020; Manosalvas-Paredes et al. 2020), a current practice approach was used for the conventional solution.

In some cases (5 papers), scenarios were used to compare innovative and conventional construction solutions and thereby consider uncertain aspects related to maintenance frequency, such as maintenance budget (Mauro and Guerrieri 2016; Guerrieri et al. 2020), choice of maintenance practice (Santos et al. 2017b), and material performance (Ma et al. 2019; Dolci et al. 2020).

4 Discussion

Assessment of future maintenance is a challenge in infrastructure LCA due to infrastructures’ long lifetimes and dynamic performance. This study provides a basis for evaluating the relevance of approaches to calculate maintenance related impacts in different decision-contexts and critically

discuss the method choice. Results can be used to suggest what approach to use in a LCA supporting a specific decision-context. The discussion focuses on the use of different approaches in transport infrastructure policy and procurement, two decision-contexts where the use of infrastructure LCA is rapidly expanding.

4.1 Use of the approaches in policy and in procurement

The approaches identified in the literature review have different characteristics. Considering that a LCA conducted in a specific decision-context may need to fulfil specific requirements, the approaches identified are more or less relevant in decision-making. Since the papers reviewed rarely expressed which decision the results were intended to support, they could not be used to determine the relevance of the approaches in specific decision-contexts. Therefore, this section first describes how characteristics of policy and procurement contexts are defined in this study and then discusses how the approaches identified in the reviewed papers match these characteristics.

In a policy context, the LCA aims to support decisions concerning multiple projects. The aim is to provide general suggestions and it is important that the relative importance of different aspects can be identified. For example, a LCA in a policy context could aim to suggest which technical solution or type of material should be generally preferred.

In a procurement context on the other hand, the LCA aims to support a decision in a specific construction project. The aim is to choose the best technical solution or material in a specific construction project. In that case, the quantitative difference between two alternatives becomes more important than in a policy context. To allow a fair comparison, the alternatives must be evaluated using the same methodological approach (Butt et al. 2015). Further, contractors' claims about environmental performance need to be transparent and comprehensible so that the procuring agency can follow-up the claims with a reasonable amount of effort. Standardised methods that can be required by the procuring agency may therefore be useful.

4.1.1 Approaches based on current practice

Approaches representing current practice were commonly used both to determine the analysis period (by using design guidelines, expert assessments, and assessment methods or by estimating the period of use) and to estimate the maintenance frequency.

In the reviewed papers, a current practice approach was applied for analysis periods of up to 100 years (including in papers comparing alternatives with different service lives). However, in both policy and procurement, using current

practice to determine analysis period and maintenance frequency would be more representative over a relatively short time-frame when significant changes to the current situation are not expected. For long analysis periods, the development of technology and external factors is too uncertain to assume that current practice continues. For instance, the current practice approaches cannot include the effects of climate change on infrastructure. Therefore, it is suggested that LCA practitioners use current practice approaches primarily when the service life or the analysis period is relatively short. If a current practice approach is used over a long analysis period, due to for instance data availability, it is suggested that LCA practitioners apply sensitivity analysis, uncertainty analysis, or multiple scenarios to evaluate the uncertainty in the results.

A current practice approach was also applied for innovative solutions (in some cases when comparing alternatives with different service lives); however, the approach is likely more representative for conventional construction solutions (for which there are experience based evaluations, guidelines, or statistics) than for innovative solutions. If the innovative solution has not been used in practice and there is no data on its actual performance, it would be problematic to assume that current practice is a relevant approach to determine maintenance frequency or service life. Therefore, it is suggested that LCA practitioners use current practice approaches primarily for conventional construction solutions.

Regarding innovative solutions, a current practice approach may be of limited use in both policy and procurement contexts. Compared to a conventional alternative, an innovative solution could have higher production related impacts but, due to lower maintenance frequency and longer service life, lower impacts over its complete life cycle. In that case, a LCA that assumes that both alternatives have the same maintenance frequency would miss the benefits of the innovative material. Hence, if suggestions were based on LCAs that assume current practice, there would be little incentive to use and develop innovative materials with low environmental impacts.

In policy, LCA practitioners could avoid potential problems of using a current practice approach by applying sensitivity analysis, uncertainty analysis, or multiple scenarios to evaluate possible alternative outcomes (as was done in several papers in Sect. 3.5.2). Alternatively, a combination of approaches could be used. For example, a current practice approach could be applied for the conventional solution and scenarios or laboratory tests could be applied for the innovative solution (see for example papers reviewed in Sects. 3.3.2 and 3.3.4). In a procurement context, however, the same calculation method must be applied for all alternatives to compare the alternatives fairly. If a current practice approach is used in the LCA, the procuring agency

could combine LCA results with technical requirements. For example, if an innovative asphalt mixture is expected to last longer than its competitor does, LCA results *and* technical performance (verified through results from a predefined physical test) could be the basis of selection.

4.1.2 Approaches based on expert assessments

By using expert assessments (through for example surveys or interviews) to determine analysis period and maintenance frequency LCA practitioners could receive estimates that consider developments related both to climate and to innovative solutions. However, evaluations may vary between expert groups; thus, it could be hard to achieve a robust basis for comparison using expert assessments. For example, in the survey used by Mazumder et al. (2018), the experts' assessments of the crack sealant treatments' durability varied significantly. If the LCA results are to be used in a procurement setting, expert opinions could be too subjective and other methods would be more suitable. In development of policy on the other hand, where it is here suggested that LCA practitioners assess various alternatives, a large variety of opinions could be considered and expert assessments fit well into the decision framework.

4.1.3 Approaches based on modelling and laboratory tests

Modelling and laboratory tests were commonly used to estimate maintenance frequency and in a few cases used to determine analysis period (also when alternatives have different service lives). For LCA practitioners, these approaches could have benefits in both policy and procurement contexts. Modelling has been requested for use in LCA to provide better estimate of maintenance related impacts (Santero et al. 2011a). Additionally, modelling and laboratory tests can consider climate specific aspects, although the approaches were not used for that purpose in the reviewed papers. For example, performance-prediction models that consider the current local climate (see for example Hamdar et al. (2020) and Xu et al. (2019)) may incorporate scenarios for a future climate. For instance, Valle et al. (2017) and Guest et al. (2020) have investigated how climate change can be included in road LCA and incorporated climate scenarios in ME models to determine maintenance frequency of road surfaces. Moreover, in a procurement setting, modelling and laboratory tests could provide a standardised way to provide evidence of a material's performance.

However, modelling and laboratory tests also have potential limitations that LCA practitioners should consider when selecting approach. Models that are based on long-term observations of infrastructure performance face the same challenges as the current practice approaches when it comes to innovative materials and future climate change

(see Sect. 4.1.1). Therefore, in a procurement setting that involves innovative materials, the procuring agency must ensure that the models and tests provide a fair comparison of conventional and innovative materials. Additionally, performance-prediction models are not available for all materials and structures and there is a need for locally calibrated models for representative results. Hence, in many LCA, models representative of the specific construction solution may be unavailable and other approaches would be more suitable.

4.1.4 Approaches based on scenarios

Scenarios could be useful for LCA practitioners when performance is uncertain (as would be the case for many innovative solutions) and in the case where laboratory tests and performance-prediction models are inapplicable. Scenarios can be used to determine the analysis period (also when alternatives have different service lives), estimate the maintenance frequency (also for innovative solutions), and account for the effects of climate change.

In policy where the LCA aims to provide general recommendations, it is suggested that LCA practitioners compare multiple scenarios. Future scenarios regarding climate change should also be included. If results are consistent across multiple scenarios, the conclusions are more robust. Although it could be assumed that most papers reviewed are for policy purposes (since most conclude their papers by providing general suggestions), only few considered the uncertain performance by using scenarios.

In a procurement on the other hand, scenarios are more difficult to use. In a procurement setting, LCA practitioners should use previously developed consistent and generic scenarios. The use of such scenarios has also been suggested by Höjer et al. (2008) for general application in LCA. Additionally, the procuring agency could complement the LCA based requirements by policy based technical requirements on the construction.

4.2 Contribution and suggestion for further studies

4.2.1 Using ME models to predict infrastructure performance

Previous literature reviews have emphasised the lack of infrastructure performance in infrastructure LCA (Santero et al. 2011a; Inyim et al. 2016) and have suggested that research should be directed towards including material deterioration (Inyim et al. 2016) and integrating ME models (Santero et al. 2011a) in LCA. In this review, it was found that about 30% of the papers considered infrastructure performance through modelling and several of these papers used ME models. Hence, compared to findings in previous

reviews, there appears to be a trend towards increased use of performance-prediction models in infrastructure LCA.

In contrast to previous reviews, this study reviewed the specific approaches used and discussed how they could be applied in policy and procurement. Although modelling has great potential to improve performance-predictions in both policy and procurement contexts, there are potential problems when comparing innovative and conventional construction solutions (Sect. 4.1.3) that hampers a fair comparison of alternatives in a procurement setting. Thus, before implementing modelling consistently in a standardised way, more research would be required.

4.2.2 Including effects of climate change on infrastructure

The use of scenarios to capture the effect of climate change on infrastructure was investigated, something that has not been covered in previous literature reviews. Even though significant changes may be expected to the climate only few studies included scenarios of climate change and their effect on maintenance frequency. However, other papers, not part of this review, have included climate change effects in road surface LCA, comparing environmental impacts of road surfaces under different climate change scenarios (temperature and precipitation) in the USA (Valle et al. 2017) and Canada (Guest et al. 2020).

Although LCA practitioners are here suggested to consider the effects of climate change on maintenance practices, including climate change in a LCA may be challenging. For example, a multitude of climate change effects influences the infrastructure in different ways (Qiao et al. 2020). These effects are connected to significant uncertainties related to regional effects and correlations between climate change and the quantitative effect on maintenance frequency and service life (*ibid.*).

More research on developing systematic approaches to integrate future climate change in LCA for policy and procurement is therefore important. For example, more research is needed to understand the effect of climate change on infrastructure service life in different regions. Additionally, more research has been suggested to consider the consequences of combined effects (Setsobhonkul et al. 2017), extreme weather events (Setsobhonkul et al. 2017; Guest et al. 2020) and the effect of climate change on vehicles and their influence on infrastructure performance (Valle et al. 2017). Further, it has been suggested to use more climate models and apply developed methods in additional case studies (Guest et al. 2020).

4.2.3 Accounting for future scenarios in general

LCA practitioners are here suggested to use scenarios for the evaluation of results under a range of possible outcomes.

Scenarios can be used both to consider climate change and other aspects related to maintenance frequency and analysis period, such as traffic load and maintenance budget (see Sects. 3.3.4 and 4.1.4). To incorporate scenarios in LCA, the LCA practitioner could draw knowledge from the field of futures studies and papers that have suggested ways to incorporate future scenarios in LCA in general.

Höjer et al. (2008) describe how scenarios could be generally integrated in LCAs with examples from predictive scenarios (“what will happen?”), explorative scenarios (“what can happen?”), and normative scenarios (“how can a specific target be reached?”). Höjer et al. (2008) suggest that in LCA of long-lived products, for long-term decisions, and when changes in trends are expected—all characteristics of infrastructure LCA—explorative scenarios are more relevant than predictive scenarios. Additionally, explorative scenarios are useful when predictive scenarios are considered too uncertain (which in turn depends on the aim of the study and the researchers’ worldviews and perceptions) (Höjer et al. 2008), which could be the case under climate change.

In the reviewed papers that used scenarios to determine analysis period, estimate maintenance frequency, or include climate change effects, the most common scenario used was a what-if scenario (defined by Höjer et al. (2008) as a type of predictive scenario that answers the question “what will happen, on the condition of some specified event?”). Although these papers analysed results under various scenarios for external factors such as budget, traffic load, and temperature, none of the papers analysed the possible development of the external factors. Such an analysis would be, according to Höjer et al. (2008), a type of explorative scenario answering the question “what can happen to the development of external factors?”. Considering the uncertainties involved in the maintenance phase, including more explorative scenarios to assess a wide range of potential outcomes could be beneficial for LCA practitioners in the interpretation of results.

4.2.4 Reviewing additional literature

The literature search in this study was limited to comparative LCAs published in peer-reviewed scientific journals. Although this scope is considered to fairly well cover available approaches, a natural extension for future research is reviews including LCA models, certification systems, reports, standards, and guidelines. Such sources could include approaches that are not yet published in peer-reviewed journals but that could be highly relevant for understanding the practical implementation of LCA in policy and planning. Additionally, stand-alone LCAs and method development papers could be studied for other approaches and perspectives. Further reviews of each approach and decision-context could provide additional insights into the practical usability of the approaches identified in this review.

5 Conclusions

LCA is becoming used more frequently in infrastructure policy and planning. The practical relevance of methodological approaches must therefore be critically evaluated considering that a LCA may need to fulfil specific requirements placed in a decision-context. This study has provided, through a review of 92 papers, an overview of approaches to include future maintenance in comparative road and rail infrastructure LCA. Specifically, the study has reviewed approaches used to determine analysis period, estimate maintenance frequency, and include effects of climate change. These three aspects could significantly influence the results of a LCA. The relevance of the approaches identified was addressed in different comparative situations and in policy and procurement contexts.

In the reviewed literature, the analysis period was based on the infrastructure service life or guidelines for assessment methods such as LCA or LCCA. In more than half of the papers, the choice of analysis period was not described. Papers comparing alternatives that have different service lives commonly applied a joint analysis period for all alternatives. Maintenance frequency was estimated based on current practice, laboratory tests, modelling, and scenarios, both in LCA of innovative and conventional construction solutions. In about one quarter of the papers, it was not possible to determine how the maintenance frequency had been estimated. Only two papers quantified the effects of climate change on maintenance frequency and considered its influence on environmental impacts of the maintenance stage.

Based on the papers reviewed and the approaches identified in this study, suggestions for how LCA practitioners

could use the approaches are provided. In both policy and procurement, LCA practitioners are suggested to use current practice approaches primarily in LCAs of conventional materials and over relatively short analysis periods. Expert assessments, a special case of current practice approaches, could be considered too subjective for use in procurement, but could be used in a policy context to account for multiple outcomes. Through using modelling and laboratory tests, LCA practitioners could improve the estimation of maintenance frequency and service life in LCA for both policy and procurement purposes. However, the approaches may not necessarily provide a fair comparison of innovative and conventional construction solutions. In a policy context, LCA practitioners are suggested to apply multiple scenarios, including scenarios for climate change. In a procurement context, LCA practitioners are suggested to use consistent and generic scenarios that have been previously developed.

The LCA community is suggested to research the integration of other approaches than current practice in infrastructure LCA for more representative results related to innovative solutions and long analysis periods. Some examples based on this review include integration of explorative scenarios, climate change effects, and the practical application of models and laboratory tests in procurement. To further facilitate the practical implementation of LCA, literature not reviewed here, including stand-alone LCAs, literature on specific approaches and decision-contexts, reports, certification systems, standards, and guidelines, could be reviewed for additional approaches and perspectives.

Appendix

Table 4 Characteristics of the studies included in the review: type of infrastructure and type of comparison made

Road or rail	Specific type of infrastructure	Comparison made	Compare innovative and conventional construction solutions	Reference
Road	Anti-glare device	Construction material (plastic or steel)	No	Cherubini et al. (2019)
Road	Bridge	Concrete mixes	No	Al-Ayish et al. (2018)
Road	Bridge	Construction technologies	Yes	Bizjak and Lenart (2018)
Road	Bridge	Construction technologies	Yes	Cadenazzi et al. (2019)
Road	Bridge	Construction materials, reinforcement	Yes	Cadenazzi et al. (2020)
Road	Bridge	Construction alternatives (bridge designs)	No	Du et al. (2018)
Road	Bridge	Optimal maintenance actions	No	García-Segura et al. (2017)
Road	Bridge	Different types of reinforced concrete	Yes	Hajiesmaeili et al. (2019)
Road	Bridge	Two types of bridge slabs	Yes	Iwase et al. (2020)
Road	Bridge	Three alternative bridge designs	Yes	Lemma et al. (2020)
Road	Bridge	Fifteen prevention strategies	Yes	Navarro et al. (2018)
Road	Bridge	Eighteen design alternatives for a bridge	No	Navarro et al. (2019a)
Road	Bridge	Sixteen design alternatives for a bridge	Yes	Navarro et al. (2019b)
Road	Bridge	Bridge designs: concrete vs wood	Yes	O'Born (2018)
Road	Bridge	Adhesively bonded carbon fibre reinforced polymer vs steel plates	Yes	Orcesi et al. (2019)
Road	Bridge	Two optimal post-tensioned concrete box-girder bridges	No	Penadés-Plà et al. (2017)
Road	Bridge	Bridge designs: concrete vs wood	Yes	Peñaloza et al. (2018)
Road	Bridge	Two bridges (existing bridge deck vs timber-concrete composite)	Yes	Rodrigues et al. (2017)
Road	Bridge	Ultra-high performance concrete vs conventional concrete	Yes	Sameer et al. (2019)
Road	Bridge	Eight different retrofit options	No	Tapia and Padgett (2016)
Road	Bridge	Maintenance strategies	No	Xie et al. (2018)
Road	Culvert	Construction materials (different types of concrete and reinforcing)	Yes	Redaelli et al. (2019)
Road	Drainage	Construction alternatives	No	Byrne et al. (2017)
Road	Crash barriers	Four types of crash barriers: two types of wood and two types of steel	No	Noda et al. (2016)
Road	Surface road	Road surface materials	No	AzariJafari et al. (2018)
Road	Surface road	Different types of electrified roads	Yes	Balieu et al. (2019)
Road	Surface road	Different road surface materials	No	Batouli et al. (2017)
Road	Surface road	Road surface materials	No	Boonpoke et al. (2018)
Road	Surface road	Aggregate sources and asphalt mixes	No	Butt and Birgisson (2016)

Table 4 (continued)

Road or rail	Specific type of infrastructure	Comparison made	Compare innovative and conventional construction solutions	Reference
Road	Surface road	Construction materials (road surface, soil stabilisation); maintenance strategies	No	Celauro et al. (2017)
Road	Surface road	Road surface materials	Yes	Chen et al. (2016)
Road	Surface road	Maintenance strategies	No	Choi (2019)
Road	Surface road	Construction materials (road surface)	No	Choi et al. (2016)
Road	Surface road	Construction alternatives (road base thickness)	No	Chong and Wang (2017)
Road	Surface road	Construction alternatives (road base thickness)	No	Chong et al. (2018)
Road	Surface road	Construction materials (road surface)	Yes	Cong et al. (2020)
Road	Surface road	Standard paving materials vs bituminous mixtures containing recycled materials	Yes	Farina et al. (2017)
Road	Surface road	HMA ¹ concrete, jointed plain Portland cement concrete	No	Gregory et al. (2016)
Road	Surface road	Smart vs conventional motorways	Yes	Guerrieri et al. (2020)
Road	Surface road	Different road paving technologies	No	Gulotta et al. (2018)
Road	Surface road	Different road paving technologies	Yes	Gulotta et al. (2019)
Road	Surface road	Eight asphalt mixes using different binder grades and WMA ² additives	No	Hamdar et al. (2020)
Road	Surface road	Different types of aggregates and road surface materials	Yes	Hasan et al. (2020)
Road	Surface road	Maintenance strategies	No	Haslett et al. (2019)
Road	Surface road	Forty-two types of asphalt concrete and plain cement concrete	No	Heidari et al. (2020)
Road	Surface road	Reference mastic asphalt vs temperature-reduced mastic asphalt	Yes	Hofko et al. (2017)
Road	Surface road	RAP ³ and virgin mixes with different overlay thicknesses	No	Hong and Prozzi (2018)
Road	Surface road	Road surface material: asphalt vs concrete	No	Huang et al. (2018)
Road	Surface road	Maintenance options: two types of overlay	Yes	Krishna and Kumar (2020)
Road	Surface road	Three types of HMA	Yes	Landi et al. (2020)
Road	Surface road	Permeable road surface vs traditional road surface	Yes	Liu et al. (2020)
Road	Surface road	Induction healed asphalt mix vs traditional asphalt mix	Yes	Lizasoain-Arteaga et al. (2019)
Road	Surface road	Three types of road surface materials	Yes	Lu et al. (2019)
Road	Surface road	WMA and HMA	Yes	Ma et al. (2019)
Road	Surface road	Maintenance plans: pre-set or determined by embedded sensors	Yes	Manosalvas-Paredes et al. (2020)

Table 4 (continued)

Road or rail	Specific type of infrastructure	Comparison made	Compare innovative and conventional construction solutions	Reference
Road	Surface road	Road construction projects	No	Marzouk et al. (2017)
Road	Surface road	Maintenance strategies: crack sealing or filling	No	Mazumder et al. (2018)
Road	Surface road	HMA and WMA with different types of recycled materials	Yes	Praticò et al. (2020)
Road	Surface road	HMA and two types of WMA	Yes	Puccini et al. (2019)
Road	Surface road	Self-healing road vs conventional road	Yes	Rodríguez-Alloza et al. (2019)
Road	Surface road	Three technologies to produce porous asphalt mixtures	Yes	Rodríguez-Fernández et al. (2020)
Road	Surface road	Three recycled asphalt mixtures compared with a control virgin mixture	No	Saeedzadeh et al. (2018)
Road	Surface road	Maintenance strategies	Yes	Santos et al. (2017a)
Road	Surface road	WMA and HMA technologies with and without RAP	Yes	Santos et al. (2018a)
Road	Surface road	Maintenance strategies	Yes	Santos et al. (2018b)
Road	Surface road	Different types of HMA and WMA	Yes	Santos et al. (2019)
Road	Surface road	Maintenance strategies	No	Santos et al. (2020)
Road	Surface road	HMA and WMA with different RAP contents, two types of preventive maintenance	Yes	Santos et al. (2017b)
Road	Surface road	HMA with and without hydrated lime	No	Schlegel et al. (2016)
Road	Surface road	Three maintenance strategies	Yes	Simões et al. (2017)
Road	Surface road	Various surface layers, base layers, subbase layers, sewer systems, bicycle paths, footpaths	No	Trigaux et al. (2017)
Road	Surface road	Road surface alternatives (flexible, concrete, geosynthetics)	Yes	Umer et al. (2017)
Road	Bridge	Structural materials for bridge girders: steel or pre-stressed reinforced concrete	No	Wang et al. (2020)
Road	Surface road	Bitumen vs three types of polystyrene waste to substitute bitumen in asphalt	Yes	Vila-Cortavitarte et al. (2018)
Road	Surface road	Eighteen road surface designs (flexible and rigid) in nine different contexts	No	Xu et al. (2019)
Road	Surface road	Spall repair methods: conventional vs 3D-printing	Yes	Yeon et al. (2020)
Road	Surface road	Three road surface alternatives (HMA, WMA, and RAP)	No	Zheng et al. (2020)
Road	Surface road	Three preservation treatments vs “do nothing” alternative	No	Zulu et al. (2020)

Table 4 (continued)

Road or rail	Specific type of infrastructure	Comparison made	Compare innovative and conventional construction solutions	Reference
Road	Roundabout	Roundabout designs: conventional double-lane, turbo, and flower	Yes	Mauro and Guerrieri (2016)
Road	Tunnel	Design alternatives for a tunnel	No	Audi et al. (2020)
Road	Tunnel	Construction materials (road surface), lighting systems	Yes	Cantisani et al. (2018)
Road	Tunnel	Road surface: asphalt vs concrete	No	Guo et al. (2019)
Road	Tunnel, bridge, surface road	Road location alternatives	No	O'Born et al. (2016)
Road, pedestrian	Bridge	The one thousand most sustainable bridge designs	No	Penadés-Plà et al. (2020)
Road and rail	Tunnel	New drainage system vs conventional drainage system	Yes	Stripple et al. (2016)
Rail	Bridge	Construction technologies	Yes	Bizjak et al. (2017)
Rail	Bridge	Eight techniques for railway bridge transition mitigation	No	Setsobhonkul et al. (2017)
Rail	Noise and vibration mitigation measures	Four noise and vibration mitigation measures	Yes	Tuler and Kaewunruen (2017)
Rail	Sleeper	Four types of sleepers: mono-block concrete, hardwood, softwood, steel	No	Rempelos et al. (2020)
Rail	Track bed	Construction technologies	Yes	Bressi et al. (2018)
Rail	Track bed	Construction alternatives (sleepers)	Yes	Dolci et al. (2020)
Rail	Track bed	Three track systems	Yes	Krezo et al. (2016)

HMA hot mix asphalt, *WMA* warm mix asphalt, *RAP* recycled asphalt pavement

Table 5 Approach used to determine the length of the analysis period in each paper, reference used to motivate choice of analysis period, whether the paper compared alternatives with different service lives, and the length of the resulting analysis period

Approach to determine length of analysis period	Reference to analysis period	Compare alternatives with different service lives	Analysis period (years)	Reference
Combination of approaches	Reasoning based on construction practice and assessment guidelines	Yes	50	Batouli et al. (2017)
Combination of approaches	Reasoning based on previous studies	Yes	100	Cadenazzi et al. (2020)
Combination of approaches	US Federal Highway Administration's LCCA policy; common analysis period used in LCA	No	40	Choi (2019)
Combination of approaches	Local practice and US Federal Highway Administration's recommendations	No	40	Chong et al. (2018)
Combination of approaches	Match best practices for both the LCCA and the LCA	No	40	Umer et al. (2017)
Combination of approaches	Typically anticipated service duration	No	30	Yeon et al. (2020)
Design service life	Construction guidelines	No	25	Butt and Birgisson (2016)
Design service life	Emerging and current state of practice	Yes	100	Cadenazzi et al. (2019)
Design service life	Conventional service life of flexible pavements' road surfaces	Yes	20	Cantisani et al. (2018)
Design service life	Movement towards longer service life	No	50	Choi et al. (2016)
Design service life	Typical design life of Chinese motorway tunnels	No	100	Guo et al. (2019)
Design service life	Local government agency guidelines	No	30	Hasan et al. (2020)
Design service life	Design service life according to Indian standards	No	20	Krishna and Kumar (2020)
Design service life	European design standards	No	100	Lemma et al. (2020)
Design service life	Design life according to Chinese specifications	Yes	36	Liu et al. (2020)
Design service life	Required service life according to European Committee for Standardization	No	100	Navarro et al. (2018)
Design service life	Required by the Spanish Ministry of Public Works	No	100	Navarro et al. (2019a)
Design service life	Design life of the bridge	No	100	Navarro et al. (2019b)
Design service life	Initial design service life of a specific bridge	No	100	Orcesi et al. (2019)
Design service life	Design service life of the case study bridge	No	150	Penadés-Plà et al. (2017)
Design service life	Design life of the bridge in the case study	No	80	Peñaloza et al. (2018)
Design service life	European design guidelines	No	50	Rodrigues et al. (2017)
Design service life	Design service life of a bridge	No	75	Wang et al. (2020)
Design service life	Design service life	No	100	Xie et al. (2018)
Design service life, predicted performance	Compare three methods to determine service life	Yes	100	Al-Ayish et al. (2018)
Estimated by experts	Estimations by manufacturer	No	10	Cherubini et al. (2019)

Table 5 (continued)

Approach to determine length of analysis period	Reference to analysis period	Compare alternatives with different service lives	Analysis period (years)	Reference
Estimated by experts, predicted performance	Expert estimates, laboratory tests	Yes	30	Landi et al. (2020)
Fixed analysis period	Product Category Rules	No	60	Bizjak et al. (2017)
Fixed analysis period	European Commission guidelines for cost–benefit analysis	No	30	Celauro et al. (2017)
Fixed analysis period	European Commission guidelines for cost–benefit analysis	No	30	Guerrieri et al. (2020)
Fixed analysis period	US Federal Highway Administration's guidelines for LCCA of road surfaces	No	35	Heidari et al. (2020)
Fixed analysis period	European Commission guidelines for cost–benefit analysis	No	30	Mauro and Guerrieri (2016)
Fixed analysis period	WebTAG recommendations for cost–benefit analysis	Yes	60	Rempelos et al. (2020)
Fixed analysis period	Longer than in the LCCA guideline	Yes	40	Simões et al. (2017)
Fixed number of maintenance cycles	LCCA manual from California Department of Transportation	Yes	92–135	Haslett et al. (2019)
Fixed number of maintenance cycles	ISO standard for acoustics	Yes	72	Puccini et al. (2019)
Fixed number of maintenance cycles, no motivation	For some track types: specified number of renewals and renewal frequency	Yes	100–120	Krezo et al. (2016)
No motivation	Generally considered for civil engineering structures	No	100	Audi et al. (2020)
No motivation	Not specified	No	50	AzariJafari et al. (2018)
No motivation	Not specified	No	20	Balieu et al. (2019)
No motivation	Most common lifetime of new bridges	No	100	Bizjak and Lenart (2018)
No motivation	Not specified	No	Not specified	Boonpoke et al. (2018)
No motivation	Not specified	No	60	Bressi et al. (2018)
No motivation	Not specified	No	60	Byrne et al. (2017)
No motivation	Not specified	Yes	40	Chen et al. (2016)
No motivation	Not specified	No	40	Chong and Wang (2017)
No motivation	Not specified	No	Not specified	Cong et al. (2020)
No motivation	Not specified	Yes	1	Dolci et al. (2020)
No motivation	Common design life	No	80	Du et al. (2018)
No motivation	Assumptions	Yes	18–20	Farina et al. (2017)
No motivation	Design service life	No	150	García-Segura et al. (2017)
No motivation	Not specified	No	20–75	Gregory et al. (2016)
No motivation	Assumed average lifetime	No	20	Gulotta et al. (2018)
No motivation	Assumed lifetime	No	20	Gulotta et al. (2019)
No motivation	Not specified	No	100	Hajiesmaeili et al. (2019)
No motivation	Estimated design life	No	20	Hamdar et al. (2020)
No motivation	Not specified	No	20	Hofko et al. (2017)
No motivation	"As customary"	No	40	Hong and Prozzi (2018)
No motivation	Not specified	Yes	30	Huang et al. (2018)
No motivation	Not specified	No	50	Iwase et al. (2020)

Table 5 (continued)

Approach to determine length of analysis period	Reference to analysis period	Compare alternatives with different service lives	Analysis period (years)	Reference
No motivation	Assumed	No	30	Lizasoain-Arteaga et al. (2019)
No motivation	Not specified	Not specified	Not specified	Lu et al. (2019)
No motivation	Design life	No	15	Ma et al. (2019)
No motivation	Not specified	No	30	Manosalvas-Paredes et al. (2020)
No motivation	Not specified	No	50	Marzouk et al. (2017)
No motivation	Not specified	Yes	35	Mazumder et al. (2018)
No motivation	Not specified	Yes	40	O'Born et al. (2016)
No motivation	Not specified	No	100	Penadés-Plà et al. (2020)
No motivation	Assumed	No	20	Praticò et al. (2020)
No motivation	Not specified	Yes	100	Redaelli et al. (2019)
No motivation	Not specified	Yes	45	Rodríguez-Alloza et al. (2019)
No motivation	Not specified	Not specified	Not specified	Rodríguez-Fernández et al. (2020)
No motivation	Not specified	Yes	50	Saeedzadeh et al. (2018)
No motivation	Not specified	No	90	Sameer et al. (2019)
No motivation	Not specified	No	50	Santos et al. (2017a)
No motivation	Not specified	No	30	Santos et al. (2018a)
No motivation	Not specified	No	50	Santos et al. (2018b)
No motivation	Not specified	No	30	Santos et al. (2019)
No motivation	Not specified	No	30	Santos et al. (2020)
No motivation	Not specified	No	50	Santos et al. (2017b)
No motivation	Expected life span	No	50	Schlegel et al. (2016)
No motivation	Approximate lifespan	No	50	Setsobhonkul et al. (2017)
No motivation	Not specified	Yes	60	Stripple et al. (2016)
No motivation	Not specified	No	75	Tapia and Padgett (2016)
No motivation	Not specified	Not specified	Not specified	Tuler and Kaewunruen (2017)
No motivation	Not specified	Not specified	Not specified	Vila-Cortavitate et al. (2018)
No motivation	Not specified	No	50	Xu et al. (2019)
No motivation	Not specified	No	20	Zheng et al. (2020)
No motivation	Not specified	No	30	Zulu et al. (2020)
Period of use	Previous studies	Yes	40	Noda et al. (2016)
Period of use	Construction documents	No	60	O'Born (2018)
Service life of adjacent infrastructure	Average technical life span of sewer pipes	No	60	Trigaux et al. (2017)

Table 6 Approach used to determine the maintenance frequency in each paper and the references used to estimate maintenance frequency

Approach used to estimate maintenance frequency	Reference to maintenance frequency	Reference
Current practice	Expert estimations	Audi et al. (2020)
Current practice	Quebec transport government	AzariJafari et al. (2018)
Current practice	Maintenance plans from Florida Department of Transportation	Batouli et al. (2017)
Current practice	Regular maintenance by the Slovenian Roads Operator	Bizjak and Lenart (2018)
Current practice	Regular maintenance by Croatian railways	Bizjak et al. (2017)
Current practice	Construction guidelines	Butt and Birgisson (2016)
Current practice	Illinois Tollway standards of practice	Byrne et al. (2017)
Current practice	Routine maintenance based on previous study	Cantisani et al. (2018)
Current practice	Estimations by manufacturer	Cherubini et al. (2019)
Current practice	Missouri Department of Transportation	Choi et al. (2016)
Current practice	Statistics, experts	Du et al. (2018)
Current practice	Chinese regulations	Guo et al. (2019)
Current practice	"Currently practiced in the field"	Hasan et al. (2020)
Current practice	LCCA manual from California Department of Transportation	Huang et al. (2018)
Current practice	Interviews with design and construction companies and bridge designers; legal service life of wooden bridges	Iwase et al. (2020)
Current practice	Design specifications from transport agencies	Krishna and Kumar (2020)
Current practice	Standard maintenance practices in European motorway administrations	Lemma et al. (2020)
Current practice	Specifications of maintenance for asphalt surfaces and permeable asphalt	Liu et al. (2020)
Current practice	Various studies, aiming to find the period of use	Noda et al. (2016)
Current practice	National road requirements	O'Born et al. (2016)
Current practice	Expert estimation by the design company	Peñaloza et al. (2018)
Current practice	Representing French practice	Santos et al. (2018a)
Current practice	According to French practice	Santos et al. (2019)
Current practice	According to French practice	Santos et al. (2020)
Current practice	Reference to previous study	Umer et al. (2017)
Current practice	Earlier study referring to Washington State Department of Transportation policy	Wang et al. (2020)
Current practice, not possible to determine	National road requirements, assumptions	O'Born (2018)
Current practice, laboratory tests	For the conventional solution: expert estimates. For the innovative solution: laboratory tests (laboratory prepared specimens and cores from full-scale application)	Landi et al. (2020)
Current practice, laboratory tests	For the conventional solution: expert estimates. For the innovative solution: laboratory tests (the authors of this review could not trace the method from the original references)	Lizasoain-Arteaga et al. (2019)
Current practice, laboratory tests	Expert assessment and previous studies; laboratory tests based on embedded sensors applied to the road surface in a testing facility	Manosalvas-Paredes et al. (2020)
Current practice, modelling	Interviews and on-site observations; previous studies based on a model to forecast maintenance needs on the track network	Krezo et al. (2016)
Current practice, modelling	Reasoning based on a survey (experts) and a literature review (mix of modelling and monitored test sections)	Mazumder et al. (2018)
Current practice, scenario	Italian standards, previous studies, scenarios related to material performance	Dolci et al. (2020)
Laboratory tests	Full-scale application at a road surface testing facility, cores analysed in laboratory	Saeedzadeh et al. (2018)
Modelling	Chloride induced corrosion	Al-Ayish et al. (2018)

Table 6 (continued)

Approach used to estimate maintenance frequency	Reference to maintenance frequency	Reference
Modelling	Performance-predictions by finite element simulations	Balieu et al. (2019)
Modelling	Integrated model (based on laboratory tests) proposed in previous study	Bressi et al. (2018)
Modelling	Life-365 software	Cadenazzi et al. (2019)
Modelling	Life-365 software	Cadenazzi et al. (2020)
Modelling	“ME pavement design guide” software	Chen et al. (2016)
Modelling	Road surface design software from Korea Pavement Research Program, “Pavement Condition Index”	Choi (2019)
Modelling	“ME pavement design guide” software	Chong and Wang (2017)
Modelling	“ME pavement design guide” software	Chong et al. (2018)
Modelling	“Pavement condition index”	Cong et al. (2020)
Modelling	Modelling of corrosion propagation	García-Segura et al. (2017)
Modelling	“ME pavement design guide” software	Gregory et al. (2016)
Modelling	Compare three performance measures	Hamdar et al. (2020)
Modelling	Road surface design software (ME), previous studies reporting results from observations and laboratory tests on trial sections	Haslett et al. (2019)
Modelling	Including dynamic programming, Monte Carlo analysis, and TOPSIS to find the best road surface alternative	Heidari et al. (2020)
Modelling	Road surface deterioration model developed in a previous study	Hong and Prozzi (2018)
Modelling	Use framework from a previous study which integrates LCA with a “ME pavement design guide” model	Lu et al. (2019)
Modelling	Fickee model (time-dependent evaluation of chloride concentration in concrete)	Navarro et al. (2018)
Modelling	Fickee model (time-dependent evaluation of chloride concentration in concrete)	Navarro et al. (2019a)
Modelling	Fickee model (time-dependent evaluation of chloride concentration in concrete)	Navarro et al. (2019b)
Modelling	Based on the extended fatigue strength curve in Eurocode EN 1993–1-9 7.1	Orcesi et al. (2019)
Modelling	Degradation curves (developed in a previous project) for functional characteristics vs traffic; American Association of State Highway and Transportation Officials method (“present serviceability index” over time)	Puccini et al. (2019)
Modelling	International Federation for Structural Concrete Model Code for Service Life Design	Redaelli et al. (2019)
Modelling	Software Alize & 3D-move	Rodríguez-Fernández et al. (2020)
Modelling	Performance-prediction model from Virginia Department of Transportation; optimisation to determine optimal maintenance schedule	Santos et al. (2017a)
Modelling	Performance-prediction model from Virginia Department of Transportation; optimisation to maximise performance	Santos et al. (2018b)
Modelling	Relationship between “pavement condition index” and time; maintenance at a specific “pavement condition index”	Simões et al. (2017)
Modelling	Time-dependent reliability model based on bridge-investigations; optimisation to find optimal preventive maintenance schedule	Xie et al. (2018)
Modelling	“ME pavement design guide”	Xu et al. (2019)
Modelling	“Pavement condition index” and “riding quality index” over time based on previous studies	Zheng et al. (2020)
Not possible to determine	A proportion of original surface layer	Boonpoke et al. (2018)

Table 6 (continued)

Approach used to estimate maintenance frequency	Reference to maintenance frequency	Reference
Not possible to determine	Assumptions	Farina et al. (2017)
Not possible to determine	Assumed maintenance plans	Gulotta et al. (2018)
Not possible to determine	The reference provided does not support the maintenance frequency mentioned	Gulotta et al. (2019)
Not possible to determine	No references provided	Hajiesmaeili et al. (2019)
Not possible to determine	No references provided	Hofko et al. (2017)
Not possible to determine	Not specified	Marzouk et al. (2017)
Not possible to determine	No reference provided	Penadés-Plà et al. (2017)
Not possible to determine	Reference to a previous study that provides no reference to the maintenance scenario	Penadés-Plà et al. (2020)
Not possible to determine	The reference provided does not support the maintenance frequency mentioned	Praticò et al. (2020)
Not possible to determine	No reference provided	Rodrigues et al. (2017)
Not possible to determine	No reference provided	Rodríguez-Alloza et al. (2019)
Not possible to determine	Reference could not be accessed	Sameer et al. (2019)
Not possible to determine	Previous studies that could not be accessed	Setsobhonkul et al. (2017)
Not possible to determine	Estimated maintenance frequency	Stripple et al. (2016)
Not possible to determine	Reference to previous study that in turn includes an assumed maintenance frequency	Tapia and Padgett (2016)
Not possible to determine	Reference could not be accessed	Trigaux et al. (2017)
Not possible to determine	References to previous studies that could not be accessed	Tuler and Kaewunruen (2017)
Not possible to determine	Not specified	Vila-Cortavitarte et al. (2018)
Not possible to determine	No reference provided	Yeon et al. (2020)
Not possible to determine	No reference provided	Zulu et al. (2020)
Not possible to determine, current practice	For some materials, reference could not be accessed or assumptions were made; for other materials references to previous studies based on expert assessments	Schlegel et al. (2016)
Scenario	Scenarios based on maintenance budget	Celauro et al. (2017)
Scenario	Scenarios based on maintenance budget	Mauro and Guerrieri (2016)
Scenario	Network Rail Vehicle and Track Interaction Strategic Model based on observations from UK routes; scenario based on traffic load	Rempelos et al. (2020)
Scenario	Scenarios based on maintenance practices: current practice vs preventive maintenance	Santos et al. (2017b)
Scenario, modelling	Scenarios based on maintenance budget for the asphalt; crash probability for the crash barrier	Guerrieri et al. (2020)
Scenario, modelling	“Pavement condition index” deteriorating model; scenarios based on material performance	Ma et al. (2019)

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