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Global warming potential of pavements

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Abstract
Pavements comprise an essential and vast infrastructure system supporting our transportation network, yet their impact on the environment is largely unquantified. Previous life-cycle assessments have only included a limited number of the applicable life-cycle components in their analysis. This research expands the current view to include eight different components: materials extraction and production, transportation, onsite equipment, traffic delay, carbonation, lighting, albedo, and rolling resistance. Using global warming potential as the environmental indicator, ranges of potential impact for each component are calculated and compared based on the information uncovered in the existing research. The relative impacts between components are found to be orders of magnitude different in some cases. Context-related factors, such as traffic level and location, are also important elements affecting the impacts of a given component. A strategic method for lowering the global warming potential of a pavement is developed based on the concept that environmental performance is improved most effectively by focusing on components with high impact potentials. This system takes advantage of the fact that small changes in high-impact components will have more effect than large changes in low-impact components.

Keywords: pavement, life-cycle assessment, cement, concrete, asphalt, greenhouse gas, global warming potential, fuel consumption, albedo, carbonation, traffic delay

S Supplementary data are available from stacks.iop.org/ERL/4/034011

1. Introduction

Annually, nearly $150 billion and 320 million tonnes of raw materials are invested into the construction, rehabilitation, and maintenance of pavements in the United States [1, 2]. This is for a network that covers over eight million lane-miles while supporting three trillion vehicle-miles each year [3]. However, given the vast span of this infrastructure system, surprisingly little is known about its impact on the environment. Previous pavement life-cycle assessments (LCAs) have included only a few of the many components of the pavement life cycle (e.g., [4–6]), thus painting an incomplete and inaccurate picture of the environmental impacts. A few LCAs have ventured beyond the *status quo* to include traffic delay, roadway lighting, or carbonation within their scope (e.g., [7–9]), but even with their inclusion, key components are still missing [10].

Understanding the mechanisms by which pavements affect the environment is an imperative step towards improving their environmental performance. The International Organization for Standardization 14040 series governing the application of LCAs asserts that 'LCAs can assist in identifying opportunities to improve the environmental performance of products at various points in their life cycle' [11]. For pavements, the lack of understanding regarding the impact of many life-cycle components jeopardizes the functionality of current LCAs. For instance, there is no concept as to whether materials, onsite equipment, or traffic delay is the dominant component, or whether they contribute relatively comparable impacts. Understanding the relative importance of each component

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will provide valuable insight into best-practice methods to improving environmental performance.

The inability to create a comprehensive representation of the pavement life cycle is not necessarily a function of arbitrary boundaries or intellectual neglect; the dearth of available data and research is a fundamental contributor as well. In particular, the use phase is an especially enigmatic part of the life cycle that requires exploration into disparate regions of scientific literature to uncover existing information. Moreover, once uncovered, the existing information has shown to be very much a work in progress and is currently stronger in concept than it is in practice. Although many research areas are still maturing and may include large uncertainties, there is still benefit to understanding the range of potential impacts for each life-cycle component. Even order of magnitude estimates will provide insight regarding the importance of a given component relative to the rest of the life cycle. This knowledge will help identify the most efficient and effective approaches to improving the environmental performance of a pavement.

2. Methodology

2.1. Components

The pavement life cycle consists of five phases: materials, construction, use, maintenance, and end of life. Each phase is comprised of various components, each of which represents a unique interaction between pavements and the environment. These components are as follows:

(1) materials extraction and production;
(2) transportation;
(3) onsite equipment;
(4) traffic delay;
(5) concrete carbonation;
(6) roadway lighting;
(7) albedo (urban heat island and radiative forcing);
(8) rolling resistance (pavement structure and roughness).

Phases include two or more components, some of which are shared between different phases (e.g., transportation is used in the materials, maintenance, and end-of-life phases, and onsite equipment is used in the construction, maintenance, and end-of-life phases). The following paragraphs briefly describe the components. More detailed information is documented in section S1 of the supplemental information (available at stacks.iop.org/ERL/4/034011), and an involved description of their roles in the pavement life cycle can be found in [10].

Materials extraction and production consists of the processes needed to manufacture pavement materials. This includes not only the mixing at the asphalt or concrete plant, but the entire upstream supply chain needed to produce each material.

Transportation is needed to move pavement materials to and from production facilities and the project site. Transportation can occur on several different modes (i.e., barge, rail, or truck), and distances can vary widely based on project location.

Onsite equipment includes the equipment needed to construct the pavement at the project location. Examples of onsite equipment are pavers, dozers, and millers. Off-site equipment used in the production of pavement materials are accounted for in the materials extraction and production component of the life cycle.

Traffic delay occurs when construction-related activities (e.g., lane closures, detours) change the normal flow of traffic. The impact from traffic delay is measured as the difference between normal and construction conditions. Traffic delay varies widely based on location parameters (e.g., traffic volume, capacity) and pavement design parameters (e.g., intensity of construction activities, maintenance frequency).

Concrete carbonation is a naturally occurring phenomenon that sequesters a portion of the CO_2 that was liberated during calcination. The rate of carbonation varies based on concrete properties and the exposure to the environment.

Roadway lighting is used to illuminate some pavements. The amount of lighting required varies based on the reflective properties of the surface material. In general, lighter materials require less lighting than darker materials.

Albedo refers to the solar reflectance of a pavement. Pavements with higher albedos reduce global warming potential by mitigating the urban heat island effect and by increasing the radiative forcing of the surface.

Rolling resistance is one of the forces resisting vehicle movement. Both the pavement structure and the pavement roughness affect the rolling resistance, thus altering the fuel economy of the supported traffic.

2.2. Evaluation approach

The environmental impact examined is global warming potential (GWP) as measured by units of carbon dioxide equivalents (CO_2e). When inventoried, methane (CH_4), nitrous oxide (N_2O), and other greenhouse gases are normalized into units of CO_2e using a 100 year timescale [12]. Other environmental metrics, such as energy consumption, conventional air pollutants, and water pollutants, are not considered here in order to keep a reasonable scope. It is recommended that future research be focused on other metrics, as they are important environmental indicators.

In order to compare the components against one another, impacts are defined per a functional unit of one lane-kilometer with a standard lane width of 3.6 m, resulting in 3600 square meters of surface area. Impacts are analyzed using a 50 year analysis period, which allows the impact from each component to fully materialize (e.g., carbonation, whose impact rate changes over time; see section S1.5 in the supplemental information available at stacks.iop.org/ERL/4/034011). Fifty years is also a commonly used analysis period in previous pavement LCAs (e.g., [6, 7, 13]). This functional unit purposely does not describe the traffic, climate, structure, or other characteristics of the pavement. Leaving these descriptors as variables rather than constants forces the results to account for their fluctuations in different situations.

In order to capture both the variability of pavements and uncertainty in the values, two ranges are determined: (1) a probable range of values based on the best estimates, and (2) an extreme range of values based on outlying data and less likely

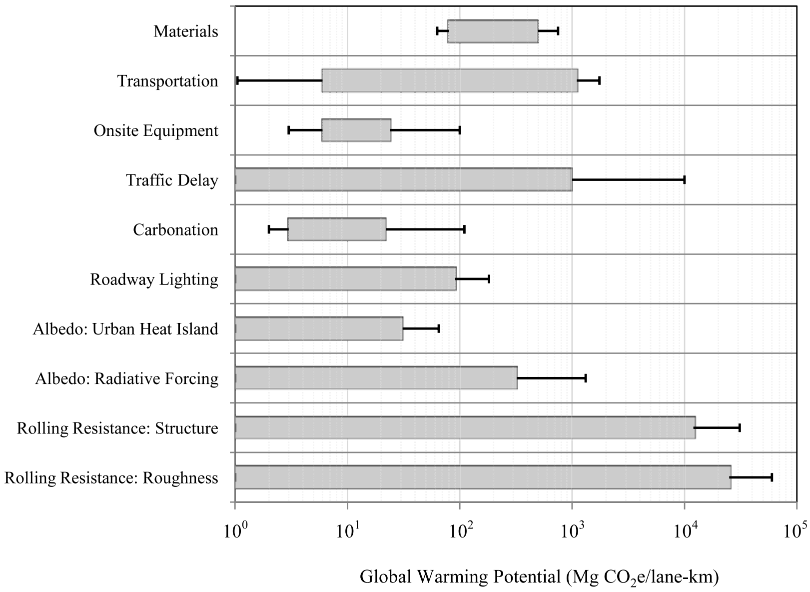

Figure 1. GWP impact ranges for components of the pavement life cycle (data not given a positive/negative designation).

(but still possible) scenarios. This double-ranged technique is in part a consequence of the vague functional unit used to define the pavement, which describes only its dimensions in the analysis period. As previously mentioned, notably missing from this functional unit is the location of the pavement and the traffic that the pavement supports. The impact of a given component can shift wildly based on these and other characteristics. Without knowledge of this information, the range needs to respect the conceivable minimum and maximum values. The use of two ranges technique is also useful in incorporating uncertain data points into the range estimates (using the extreme values) without compromising the integrity of the probable values.

A combination of published values, theoretical calculations, and scientific judgment are used to estimate the range of values that can be expected for each component of the pavement life cycle. A series of distinct literature reviews has collected the information currently available for each subject. The data uncovered in the reviews has been used to estimate GWP ranges for each component. The data, sources, and calculations supporting these ranges are documented in the supplemental information (available at stacks.iop.org/ERL/4/034011).

3. Impact ranges of the components

Like many other environmental indicators, the GWP impact is most useful when evaluated in an appropriate context. For example, claiming that some process emits 100 megagrams (Mg) of CO_2 means very little until it is juxtaposed against other germane information, such as a comparable process or a system of processes. For this exercise, the system of processes is the life cycle of a one lane-kilometer section of pavement over 50 years. The background information and numerical ranges detailed in the supplemental information (available at stacks.iop.org/ERL/4/034011) describe the components within that system. The results presented here look at those components collectively in order to better understand the pavement life cycle and identify the most promising areas for environmental improvement.

3.1. GWP ranges

The ranges of CO_2e emissions for each component of the pavement life cycle are shown in figure 1. The thick, gray bars represent the probable ranges and the thin, black lines represent the extreme ranges. An important note is that the data are not given a positive or negative designation due to the variability of existing or alternative conditions. Some components (e.g., albedo, rolling resistance) need a baseline pavement in order to make sense. Depending on where that baseline is set, the pavement properties could offer a net environmental benefit or drawback. Because of this complexity, the results are presented generically in terms of the component's impact and are without a specific sign. Also of note is the use of a base-10 logarithmic scale due to the large range of values. The supplemental information (available at stacks.iop.org/ERL/4/034011) contains the supporting details behind figure 1.

The results presented in figure 1 demonstrate the large range of impacts that are possible for the components of the pavement life cycle. The GWP impact ranges from negligibly small to 60 000 Mg of CO_2e per lane-kilometer over 50 years. Some components, such as onsite equipment and carbonation, appear to be relatively small contributors to the overall impact, while others, such as rolling resistance, can have a dominating impact under certain circumstances. However, definitively ranking the components by their impact level is problematic due to the frequent overlapping of the ranges. Without any other details regarding the specific structure and location of the pavement, it is impossible to definitively state which component has a greater impact than the next.

Table 1. GWP priority ranks and impact scenarios.

Priority rank	Life-cycle component	Ideal GWP scenario	Worst GWP scenario
1	Rolling resistance: roughness	Smooth pavements with low vehicle traffic.	Rough pavements with high vehicle traffic.
	Rolling resistance: structure	High stiffness pavement structures on low-traffic sections. Low truck traffic (AADTT).	Low stiffness pavement structures on high-traffic sections. High AADTT.
2	Traffic delay	Pavement sections with low traffic or where capacity is much higher than demand. Sections with readily available detours. Use of lane closures during off-peak traffic periods.	Pavement sections with high traffic or where capacity is comparable to demand. Sections where detours are not readily available. Lane closures occur during peak traffic periods.
	Transportation	Low overall material demand. Locally available materials, especially aggregates. Use of *in situ* recycling strategies. Any long-distance travel utilizes efficient transportation modes.	High overall material demand. Materials need to be shipped over long distances, especially aggregates. Long-distance travel using inefficient modes. Use of virgin materials for each process.
	Materials	Pavements with low structural demands (e.g., low AADTT, temperate climate) that require less material. Use of recycled or other low-impact materials. High quality construction practices that facilitate longer service lives.	Pavements with high structural demands (e.g., high AADTT, extreme climate) that require more material. Use of virgin materials. Low quality construction practices that decrease pavement service lives.
	Albedo: radiative forcing	High albedo pavements (e.g., fresh concrete).	Low albedo pavements (e.g., fresh asphalt).
3	Roadway lighting	Light colored pavements on freeway or other roadway classifications with low lighting requirements.	Dark colored pavements on arterials or other roadway classifications with high lighting requirements.
	Albedo: urban heat island	High albedo (e.g., fresh concrete) pavements in sparsely populated areas. Temperate climates with low air conditioning demand.	Low albedo pavements (e.g., fresh asphalt) in dense urban environments. Hot weather climates with high air conditioning demand.
	Carbonation	High surface area of exposed concrete. Concrete with high cement content and porosity. High humidity and temperature climates. Concrete rubblized and exposed at the end of its life.	Concrete surface is buried under other pavement layers. Concrete has a low cement content and porosity. Low humidity and cold temperature climates. Left intact at its end of life.
	Onsite equipment	Projects with few construction activities over the life cycle. Use of off-site processes (allocated to 'materials') to manufacture materials. Small projects that utilize short and straightforward construction processes.	Projects with many construction activities over the life cycle. Heavy use of *in situ* recycling processes which require onsite materials production. Large projects requiring multiple layers and lifts.

This ambiguity stems from the decision to use a vague functional unit which captures a large breadth of pavements, but does not precisely describe an individual pavement. The results demonstrate that the context provided by the material types and volumes, traffic levels, maintenance schedules, and other project-specific information is critical to understanding which components of the life cycle are the most important from a GWP perspective. Because the impact is context-sensitive, there is no single component that can be considered the least or most influential under all circumstances.

3.2. Analysis

Even without the benefit of a comprehensive functional unit, the results presented in figure 1 serve as a valuable cornerstone for improving the environmental performance of a pavement. Regardless of context, knowing the *potential* impact that a component could have on the GWP helps define which aspects of the pavement should be prioritized in the evaluation process. The most rational approach to improving the environmental performance of a pavement is to address life-cycle components with the highest-impact potential. Small changes in high-impact components will lead to large overall improvements, while large changes in low-impact components may be insignificant relative to the total impact. Rolling resistance (associated with pavement structure and roughness) has the highest-impact potential, so it is reasonable to prioritize that component over those with lower-impact ceilings. If a cursory evaluation of rolling resistance for a given pavement section finds that it will be small or otherwise not meet its potential impact (which may be the case for a pavement that

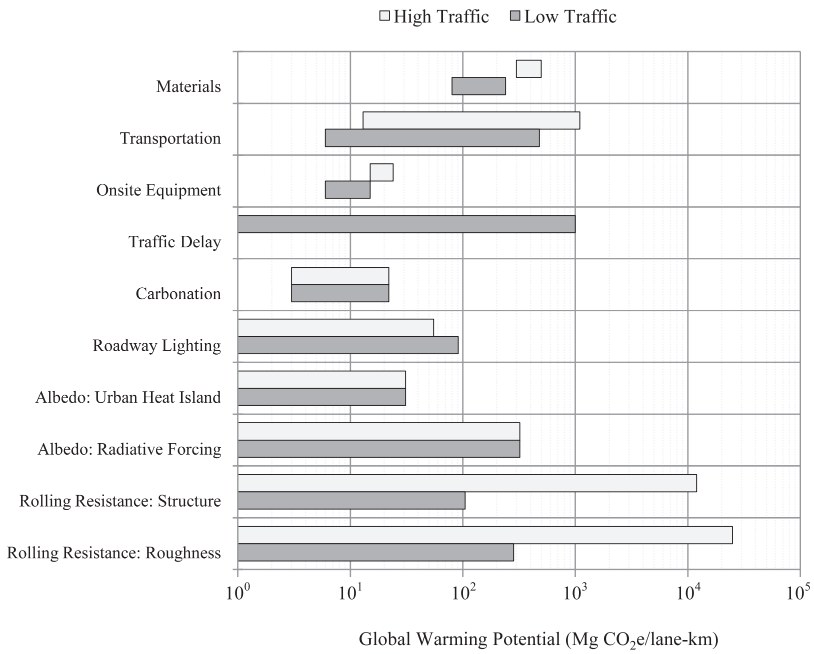

Figure 2. Comparison of GWP ranges for low- and high-traffic pavements.

only supports a low-traffic volume), then the focus should shift towards another component with high-impact potential, such as materials, transportation, or traffic delay.

Table 1 groups the pavement life-cycle components into three categories based on their GWP impact potential, termed their 'priority rank'. Also provided are the ideal and worst case GWP scenarios, which loosely describe the situations where the impact will be most mild or profound for each component. The table blends the impact potential with general pavement and project details in order to create an efficient approach to improving the GWP of a pavement. The priority rank categorization identifies where the analysis should begin, while the scenarios serve to contextualize and individualize the analysis for a given project. For pavements that match, or come close to matching, the criteria described in the worst scenario, it is likely that improvements can be made to that component. Conversely, if a pavement is already near the ideal scenario, then it may be more effective to focus efforts on other life-cycle components.

The method proposed in table 1 provides a starting point for an analysis and addresses the differences in potential that exist between components, but does not explore the feasibility of implementing a change. Cost and other barriers may prevent the improvement of certain components. The objectives of a project (e.g., a percentage reduction in GWP) may also affect which components are chosen for improvement. The method is intended to be an iterative process where each component is systematically analyzed, then implemented or ignored based on contextual information and project constraints.

A related note is the interdependency between many of the components. For example, optimizing fuel consumption by maintaining smooth pavements throughout the life cycle may increase the frequency of maintenance activities over the life cycle. In turn, this would increase the impact from materials, transportation, onsite equipment, and traffic delay components. Because the environmental gains from reduced fuel consumption are potentially large, the aggregated marginal impact from the other components may very well be small in comparison, making the focus on smoothness justified. However, there are undoubtedly cases where impact improvements for one component do not outweigh the consequential impact increases for other, related components.

Ultimately, a pavement LCA will need to quantify the entire life cycle in order to be considered fully comprehensive. The approach proposed in table 1 does not displace that need, but rather supplements the LCA process by identifying which components of the life cycle can lead to significant GWP changes under certain circumstances. The approach acknowledges that a marginal improvement in two different components can lead to impacts that differ by orders of magnitude. This disparity supports the notion that the components themselves are not equal and should not be treated as such—an ideal which is embodied in the priority ranking system.

3.3. High- and low-traffic sensitivity

One of the most influential variables is the traffic level that the pavement supports. Traffic has an obvious direct effect on the impact of rolling resistance and traffic delay, but also has an indirect effect on materials, transportation, onsite equipment, and carbonation due to the lower structural requirements for low-volume roads. It also alters the lighting requirements by changing the functional classification of a roadway. The only life-cycle components entirely unaffected by traffic volume are the urban heat island and radiative forcing components—both of which are a function of the pavement albedo.

Figure 2 shows a scenario of a low- and high-traffic pavement section. The purpose of the figure is to demonstrate the effect that one variable can have on the life-cycle footprint of a pavement. The calculations and assumptions supporting figure 2 are found in section S2.2 in the supplemental information (available at stacks.iop.org/ERL/4/034011). The high-traffic pavement is a busy freeway with heavy truck traffic. The low-traffic pavement is a local road that primarily supports passenger vehicles.

When comparing the impact ranges in figure 2, the opposing scenarios show that the traffic level of the pavement significantly affects the best-practice methods to improving the pavement. Whereas rolling resistance and traffic delay are potentially high GWP components for high-traffic pavements, their impact is significantly diminished for low-traffic pavements. Materials, transportation, and radiative forcing have at least a comparable impact to that of rolling resistance for the low-traffic scenario. The decrease in impact for rolling resistance would be even more pronounced if a very low-traffic road was considered, such as a local pavement with only a handful of vehicles per day. The current low-traffic scenario is based on the 5th percentile for the California highways and still supports a considerable amount of traffic (426 vehicles, 35 trucks per day).

The differences in potential impact of the low- or high-traffic pavements demonstrate the sensitivity of the recommended improvement strategy to changes in project variables. The results will also be sensitive to other inputs, such as the pavement structure and location. As more project details are included in the analysis, the appropriate improvement strategy will become more apparent.

3.4. Uncertainty

The decision framework described in table 1 is notably missing a discussion of uncertainty characteristics. As discussed separately in the supplemental information (available at stacks.iop.org/ERL/4/034011), the range of values for a given component is dependent upon the accuracy of the existing research as well as the contextual details regarding the pavement (e.g., location, traffic level, design). The existing research for many of the components is not in agreement regarding a specific value, making the range of values necessarily larger in order to account for this variability. Other components have so little research compiled on them that numerical quantifications are relegated to only a few point values, making the uncertainty even more difficult to characterize. In general, the components that have been omitted from most of the previous LCAs (traffic delay, carbonation, roadway lighting, albedo, and rolling resistance) suffer from research deficiencies that complicate their inclusion in a quantitatively-demanding application such as LCA. In some cases (e.g., rolling resistance), the lack of accuracy is compounded by the high potential impact: even a small miscalculation can critically alter the results and conclusions of an assessment.

The uncertainty of the data is serious enough that it changes the way the components should be included in an analysis. When comparing alternative pavement designs, it may be difficult to translate subtle differences into meaningful environmental values. This is perhaps the reason why existing pavement LCAs routinely come to contradictory conclusions: the differences between the alternatives are outweighed by the variability in the environmental factors. Alternatives are generally concluded to be more environmentally friendly based on only marginal differences in impact and thus might be outside of uncertainty bounds.

Uncertainty is difficult to capture but needs to be factored into the decision-making process. In practice, the rationale supporting a conclusion should be based on a large-enough difference in impact so that it is outside any uncertainty bounds that may exist. The fact that the difference in impact between components can vary by orders of magnitude (see figure 1) works in favor of pavements, as a difference measured on that scale is almost surely greater than the uncertainty.

4. Discussion

This research has examined the mechanisms by which the components of the pavement life cycle impact the environment and estimated the potential magnitude of those impacts. Previous pavement LCA research has excluded many of these components from their assessment frameworks, thus overlooking valuable opportunities to reduce environmental impact. It is important to understand that the ranges presented in figure 1 are magnitude estimates. They are not intended to be precise quantifications, but rather to demonstrate the large differences in potential impact that exist between components. The background material supporting the calculated values is equally important, as it reveals which variables affect the impact of a given component. Assessment boundaries will ultimately be chosen by the details and needs of a project, but a heightened understanding of the important issues ensures that those boundaries are determined using the most comprehensive information available.

Even with the varying uncertainty surrounding each component, there is still value in synthesizing the information to provide insight into how each component compares with others in the life cycle. The results show that GWP spans an immense range of values, ranging from negligibly small to 60 000 Mg of CO_2e for the functional unit of one lane-kilometer over 50 years. The impact of an individual component varies based on its contextual details, such as pavement location, structure, and traffic levels. These variations make it impossible to definitively assert that a certain component has more GWP impact than another in all situations.

The solution is a compromise that incorporates context while remaining generalized enough to apply to most pavements. The system prioritizes which components should be evaluated first based on their potential impact and then decides whether that potential is fulfilled through contextualization. The purpose of the system is to acknowledge that the components do not pose the same impact and that the differences are sometimes large enough (order of magnitudes, in some cases) to completely alter which policy and engineering changes are recommended.

The focus on climate change through the GWP metric is one of a multitude of environmental indicators that can be used to evaluate a pavement. Similar analyses using other metrics may produce significantly different results. For instance, although onsite equipment is shown to have low GWP ceiling relative to the other life-cycle components, its human health impacts will be much larger due to high exposure to carbon monoxide, particulate matter, and other local pollutants. More research is needed to understand how other impact categories are affected by the components of the pavement life cycle. As a whole, the evaluation system should adjust as future research refines the impact values for the components and expands our understanding of how pavements affect the environment.

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