Sensitivity Analysis of the Life Cycle Environmental Performance of Asphalt and Concrete Pavements

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Abstract

The goal of the present Life Cycle Assessment study is to evaluate the environmental impact over the lifetime of one square meter (the functional unit) of the two most common pavement categories: concrete and asphalt, in a robust manner that considers scenarios a variety of pavement engineering designs, varying traffic loads, and varying climatic conditions. The impact category of concern is global warming potential. The system boundary of concrete and asphalt include all cradle-to-grave life cycle phases: raw material extraction and processing; pavement construction; transportation of materials; pavement maintenance and rehabilitation; pavement use by vehicles and other use phase components; and end of life recycling and disposal. The study applies a sensitivity analysis approach to the LCA of pavements in order to determine the variability range of results in normal and extreme practice, the system parameters (such as design, climate, and traffic) that drive changes in the results, and opportunities for improving the performance in the life cycle for given engineering and policy scenarios.

Contents

Introduction

As industrial energy and resource consumption and the resulting environmental emissions rise, it is important to understand how the various industries are impacting the biosphere, as well as how these industrial emissions can be reduced. The construction, operation, and maintenance of the U.S. roadway system accounts for massive energy and resource consumption, and a significant portion of domestic greenhouse gas (GHG) emissions. The two primary types of pavements are concrete and asphalt pavements, which together make up approximately 4 million miles of public roads in the United States and 8.3 million lane miles (National Research Council, 2005). Concrete alone is the second most widely consumed substance on Earth, after water, and worldwide asphalt consumption is at over 100 million tons annually (SBI Reports, 2009).

Rivaling the environmental impact of these materials needs is the large proportion of domestic greenhouse gases released during the life cycle of pavements, especially during operation. The current system of paved roads handles a volume of traffic on the order of 3 trillion vehicle miles per year, or about 8.2 billion vehicle miles per day (DOT 2008). Road transport contributed the largest amount of GHGs of any transport mode in 2007, accounting for 82.6% of emissions from the transportation sector, and 27.3% of all GHG emissions in the U.S. (EPA, 2009).

The best tool available to calculate greenhouse gas emissions of industrial products and services is known as Life Cycle Assessment (LCA). LCA can galvanize efforts to make a product/service more sustainable, and is increasingly being used to guide the creation of public policy. It is a standard methodological procedure for accounting for the environmental impact (be they GHG emissions, or other impact categories) throughout the successive phases in a product's life cycle—including extraction of raw materials, processing those materials into valuable goods, using the product, and disposing or recycling at the end of the product's useful life. This procedure can provide information to identify the largest sources of emissions and thereby inform and prioritize efforts to mitigate the environmental impact.

While the basic LCA procedure is a standard method, in practice the application of that method can lead to widely variable results and conclusions. These results depend on the service unit selected to analyze, the assumed characteristics of the product system, the boundaries of the system, and on data quality and availability. For example, according to two separate LCAs done, contradictory results are obtained for whether asphalt or concrete consumes more energy (Horvath & Hendrickson, 1998) (Stripple, 2001). The subjective nature of the initial assumptions endangers the functionality of LCAs, and allows proponents of a given product to make favorable claims based on incomplete models. The life cycle GHG emissions of both asphalt and concrete are not well understood, due to wild variance in the results of studies. There is also no concept of the relative importance of different life cycle components and of different design parameters. A more objective basis is needed, one that does not rely on oversimplification when characterizing pavement types, and properly accounts for the diversity of design types, production, maintenance, and recycling practices,

To this end, the present study is a sensitivity analysis of a comprehensive life cycle model for pavements. Sensitivity analyses "measure how the variation in the output of a mathematical model can be apportioned, qualitatively or quantitatively, to different sources of variation in the input of a model" (Saltelli, 2008). The two broad issues that are little explored in prior studies and that the present study will attempt to evaluate are: a) the comprehensive inclusion of dominant life cycle components, or those that account for ≥5% of life cycle emissions, and b) the sensitivity of the GHG contributions of these life cycle components to various parameters (such as traffic load, climatic region, pavement albedo, etc.).

Methodology

Unit of Service

The product *unit of service*, or *functional unit*, is defined as: 1 m^2 of pavement with a 50 year lifetime. All asphalt and concrete pavements provide their useful service to vehicles through the extent of their surface, and the square meter is chosen so that it could conveniently be extrapolated to a roadway lane of any given width and length. Surface area as a reference quantity also allows for parameters such as depth and pavement composition to be varied so that the subsequent effect on the life cycle emissions can be measured and evaluated. The 50 year service life is chosen so as to be sufficiently long to require maintenance both for asphalt and concrete, and to capture the protracted effect of carbonation (Nielsen, 2007). It also conveniently allows comparison with other studies, which commonly assume 50 year lifetimes (Santero, 2009). It may, for accuracy's sake, be worth obtaining data on the actual service life of pavements and whether that is expected to change into the future. The functional unit purposely does not specify other design characteristics that could be included, such as layering and thickness specifications, traffic load, climatic zone, etc., again, so as to allow for variation of these parameters for their subsequent analysis.

Impact Category

In an LCA study, the environmental impact assessment can be done according to a number of valuation strategies. During the life cycle of the present pavement scenarios, the impact category of concern is *Global Warming Potential* (GWP), which is a measure of the ability of greenhouse gases to cause global warming once emitted into the atmosphere. All greenhouse gases are normalized according to the GWP of CO_2 over a 100 year timescale, and then summated in units of CO_2e (carbon dioxide equivalence), according to the IPCC methodology. While GWP is a preeminent issue because of concerns about anthropogenic climate change, it is important to consider other environmental impacts (such as toxic releases, water usage, etc.) in order to inform comprehensive and holistic sustainability efforts. These are not considered in the present study. GWP is also positively correlated with many other environmental impacts, such as energy consumption and inefficiency, resource extraction and scarcity, and toxic emissions to air and water.

Sensitivity Analysis

During the calculation of the GHG contribution of each life cycle component, a number of independent variables, here termed "parameters," were identified as influencing the quantity of GHGs emitted during due to that component. For example, the quantity of fly ash blended into the cement kilns can reduce the GHGs emitted in the cement production phase component by up to 20%. (C.A. Hendriks, 2004) The present study looks at a two-tiered range for the effect of these parameters on GHGs emitted, termed "normal" and "extreme." The normal range represents the current dominant practices (within 90-95% share of current practice), while the extreme range represents outlying practices and data that are still reasonably feasible. This two-tiered range is used to capture uncertainty associated with outlying values in the extreme range, without compromising the importance of the more probable, normal range. This approach is also used in other studies to ascertain the range of practices (Santero, 2009).

System Boundary

A recent literature review published looked at 12 life cycle assessment studies on pavements, and all of them failed to include all of the five primary phases: materials, construction, use, maintenance/rehabilitation, and end of life (Masanet, et al., 2010). The arbitrary inclusion of certain components within each phase also detracts from the utility of the results. This study has attempted to be as inclusive as possible in terms of life cycle phases and their components, and enumerates identified shortcomings in the "Results and Discussion" section.

The following life cycle phases and their components comprise the pavement system:

- i) Materials Extraction and Production
  - a. Binder
  - b. Aggregate
  - c. Steel Reinforcement
- ii) Construction
  - a. Mix Production
  - b. Onsite Equipment
- iii) Transportation
- iv) Maintenance and Rehabilitation
- v) Use Phase
  - a. Albedo
  - b. Carbonation
  - c. Lane Closure
  - d. Lighting
  - e. Rolling Resistance
- vi) End of Life Recycling and Disposal

Not included in the scope of this study is capital goods production (excavation and paving machinery, production plant equipment, oil refinery infrastructure, etc.).

Life Cycle Components and Associated Parameters

Materials Extraction and Production

This component includes extraction and processing of minerals that are involved in the production of asphalt and concrete pavements, and also, the differences in pavement designs. Asphalt pavements are produced from a combination of binder and aggregates, whereas concrete pavements are produced from a combination of cement binder, aggregates, water, and steel reinforcement.

Binder Material

This component includes all cradle to gate activities for the production of the pavement binder: bitumen in the case of asphalt, and cement in the case of concrete.

Bitumen

Bitumen, next to aggregates, is one of the two principal components in the production of Asphalt pavement. This element, often referred to as asphalt in the United States, is a waterproof, thermoplastic and viscoelastic adhesive which acts as a glue to hold pavement aggregates together. Bitumen, along with a number of various additives introduced to modify its properties, produces an "asphalt binder" (Youtcheff & Zupanick, 2000).

Bitumen is a residual product of the petroleum refining process; depending on origin of the crude oil, it may contain about 27 to 58 percent bitumen (Youtcheff & Zupanick, 2000). There is an order of magnitude variation in the calculation of total energy required for bitumen production and the emission from the refining process of crude oil, which is often due to the choice to include or exclude feedstock energy into its energy content. One study shows ranges from 0.4 to 6.0 GJ per ton (Zapata & Gambatese, 2005). Inclusion of feedstock energy does not affect emissions accounting, however, so the range of production practices included here are drawn from studies at Lawrence Berkeley National Laboratory, which identifies that most petroleum refineries can economically improve energy efficiency by up to 20% (Worrell & Galitsky, 2005). Doubling this approximates the extreme range of plant efficiency.

Cement

For cement, the data is drawn from prior studies, which include the following in the life cycle inventory: "Quarry and crush: extracting raw material from the earth, crushing to 5-cm (2-in.) pieces, and conveying and stockpiling. Raw meal preparation: recovering materials from stockpiles, proportioning to the correct chemical composition, and grinding and blending. Pyroprocess: processing raw meal to remove water, calcining limestone and causing the mix components to react to form clinker, cooling and storing the clinker. Finish grind: reclaiming the clinker from storage, adding gypsum and grinding to a fine powder, conveying to storage, and shipping in bulk or in bags." (Marceau 2006)

The original study included transportation of all fuels and raw materials, but this was disaggregated and added into the transportation component accordingly.
The parameters that have a significant effect on binder production emissions are: facility processing technology, combustible fuel type, and material composition. In 2007, approximately 80 percent of U.S. cement production capacity relied on a dry process technology (EPA, 2007), while the remaining wet process plants produce approximately 12% more GHG emissions per kg cement due to its increased energy needs (Worrell, Martin, & Price, 2000). While only one percent of cement plants used tires to replace coal in their kilns, GHG emissions per unit cement can be reduced by 14% due to this replacement alone (ICF Consulting, 2006). Thirdly, up to a 20% reduction in GHG

emissions per kg cement can also be obtained by partial replacement of clinker with fly ash, a waste product of the coal burning process (C.A. Hendriks, 2004). A study from the same research group at LBNL as used for the range in bitumen production emissions identified that the average plant has a cost-effective potential of reducing carbon dioxide emissions by 16%, and the theoretical potential of 28% reduction, which are respectively used here as the "normal range" and "extreme range" of practices. (Worrell, Martin, & Price, 2000).

Aggregate

Asphalt aggregate is a mixture of fine and coarse aggregate that, depending on their quality and grading, have a profound influence on the properties and performance of the mixture. The total amount of aggregates within a mix is usually a fixed percentage of the volume, however, the ratio between coarse and fine aggregates change based on the design criteria for each pavement type; coarse aggregates vary from 45 to 65 percent and fine aggregates range between 20 to 35 percent of the total mass (Mallick & El-Korchi, 2009) (AASHTO, 1993).

Aggregates dominate the asphalt mix and comprise approximately 95% of the mix by mass (AASHTO, 1993). The required energy cited in different sources for production of a ton of aggregates varies from 21 to 74 MJ per ton with a common value of 53 MJ per ton of aggregate and accounts for 100% of the energy consumed in raw materials extraction and initial transformation (Zapata & Gambatese, 2005).

Concrete aggregate consists of coarse and fine aggregates and approximately account for 80% of the concrete mixture. Based on nominal maximum size of aggregates within concrete, the percentage of cement needed to cover aggregate surface changes (Mallick & El-Korchi, 2009). The required energy for production of concrete aggregate is the same as the number mentioned above.

Steel

Since concrete is incapable of carrying the traffic-applied tensile stresses, steel is the reinforcing element in concrete pavement that carries these forces. The percentage of required steel reinforcement within the concrete pavement depends on pavement thickness and design loads and ranges from 0.60% to 0.68% of the volume (US Department of Transportation). Energy consumption of steel rebar manufacturing is the highest energy consumption in pavement production after cement manufacturing and accounts for approximately 32% of the total energy required for concrete pavement production. The energy requirements for steel production consist of raw material extraction and manufacturing and are respectively equal to 53 MJ and 19,000 MJ per ton of material (Zapata & Gambatese, 2005).

Pavement Design

Design of asphalt and concrete pavements is an extensive, complicated process that involves various factors such as sub-grade compressive strength, design traffic volume (ESALs/year), design weighting factor, design life, climate conditions, aggregate and binder types, maintenance, and numerous other factors that affect the behavior and therefore the design of each type of pavement (Small & Winston, Jun., 1988) (AASHTO, 1993).

Besides the materials required for construction of pavements, pavement thickness is crucial to the pavement design given the aforementioned constraints. Under the same loadings and design constraints for roads with low, medium, and heavy traffic, asphalt thickness varies from 5 to 7 inches, while concrete varies from 9 to 12 inches (Small & Winston, Jun., 1988) (Gui & Carlson).

Other than asphalt and concrete pavement thicknesses, base and sub-base layers play a crucial role in pavement stability and performance. Asphalt typically requires a base and a sub-base layer each 5 to 7 inches thick; whereas due to the load distribution pattern, concrete pavements only require a base layer thickness between 6 to 8 inches (Mallick & El-Korchi, 2009) (Gui & Carlson) (NAPA, 2001).

Construction

Mix Production

The asphalt mixing process involves addition of heat for two main reasons: drying of aggregates and melting of asphalt binder to a point where it can be added and mixed. The required energy for the asphalt mixing and drying of aggregates is about 360 MJ per ton of material, which is equivalent to 53 times the energy used in the concrete mixing plant: 6.8 MJ per ton of material. The main difference in the mixing energy for asphalt and concrete is due to the amount of energy required for drying of aggregates (Zapata & Gambatese, 2005).

Onsite Equipment

Consumption of energy during placement of both types of pavement depends on the amount of diesel fuel used by the onsite equipment necessary for the operation. Zapata & Gambatese offer a table of suggested equipment for pavement placement for asphalt pavement: asphalt paver, rollers, tack truck, pickup trucks, small loader, and small broom. And for concrete pavements: paver, tiner/cure machine, pickup trucks, and small loader. The energy required for asphalt pavement placement is 13 MJ per ton and almost twice this value at 34 MJ per ton of concrete pavement (Zapata & Gambatese, 2005). This difference in the placement energy is due to two main reasons: 1) the paper assumes that placement of concrete pavement requires two pavers while asphalt pavement placement requires only one paver, 2) more asphalt pavement can be placed in one hour compared to concrete pavement.

Transportation

Four transport legs are accounted for here: i) fuels and materials from quarry to bitumen/cement plant, ii) bitumen/cement and aggregate materials from source to hot mix/ready mix plant, iii) base material, steel reinforcement and hot mix/ready mix from source to paving site, and iv) transport of reclaimed material at end of life.

An average distance, standard deviation, and number of tons shipped by transport mode (truck, rail, and barge) are given for commodity “Petroleum asphalt” in the commodity flow survey of 2007, allowing estimation of the average and range of emissions from this leg (BTS, 2007). Between 2005-2008, net imported cement constituted 20.4% of apparent consumption, 22% of which comes from China, primarily by barge (U.S. Geological Survey, 2010). Less than one percent of construction aggregates are imported, with 94% of imports coming from Canada and Mexico (USGS, 2010). During this same period, average distances and standard deviation for each transport mode are given for aggregates by the US commodity flow survey (BTS, 2007). Here the distance from CAL-Bechelt operation in British Columbia, the largest gravel mine in North America in 2002, to San Francisco (1600 km), serves as a proxy for the extreme range maximum for barge transport of aggregates (Robinson, 2002). The commodity flow survey also gives transportation data for hot mix asphalt, ready mixed concrete, and steel rebar. These were also used as proxies for respective reclaimed materials at the end of life, since better data was not found.

Maintenance and Rehabilitation

The condition of a pavement degrades from the original design specification as a function of time. The "design lifetime" is the duration the pavement is expected to last before requiring rehabilitation. During the first 75% of the design lifetime, a pavement loses about 40 percent of its quality. Preventive maintenance that focuses on the pavement surface and sub-surface can be done during this time. During the remaining 25%, the quality degrades another 40% and rehabilitation is in order. The four types of rehabilitation are: reconstruction of the pavement, application of overlays, combination of recycling and overlays, and recycling (Hicks & Seeds, 2000). The loss of quality over time makes maintenance a crucial part of a pavement's life cycle, and depends on design parameters, traffic characteristics, and climate (Papagiannakis & Masad, 2008).

Maintenances and rehabilitations also have a service lifetime and require replacement after this period. Different sources cite different lifetimes for such activities; however, the range of maintenance lifetimes, depending on the faulting severity and the required treatment, varies from 5 to 12 years (Papagiannakis & Masad, 2008) (Hicks & Seeds, 2000). Also, studies suggest that asphalt pavements, based on different loadings and conditions, normally last from 13 to 16 years whereas concrete pavements, under the same loading, last from 23 to 28 years; these values vary from 7 to 20 years for asphalt pavements and 17.5 to 50 years for concrete pavements within the extreme range (Gharaibeh & Darter, 2003) (Croney & Croney, 1997). One study also shows that pavement life can be doubled in favorable conditions where asphalt pavements are covered with tree shades (McPherson & Muchnick, 2005).

Use Phase

Albedo

Albedo is a measure of how strongly the pavement surface is able to reflect sunlight. This has a two-fold effect on the greenhouse gas emissions during the use phase: through radiative forcing, and through the urban heat island effect. Radiative forcing refers to the surface's ability to reflect incoming light back out of the earth's atmosphere, which tends to cool the earth's climate system. Urban heat island refers to the pavement's effect on the ambient air temperature, which indirectly affects GHG emissions by changing the heating and cooling needs of proximal buildings.

The climate impact of radiative forcing depends only on the parameter of pavement color, and is measured on a scale of 0 (black) to 1 (white) relative to the average albedo of the earth's surface (0.3) (Goode, 2001). This value normally ranges from .05 to .20 for asphalt pavements, and from .25 to .40 for concrete pavements, and the extreme range extends to 0.80 for concrete with added whitening agents (Akbari, 1999). The global warming potential of this effect is about an order of magnitude larger than that of urban heat island.

The urban heat island effect depends both on the pavement color, as well as on features of the local urban population center that contribute to the effect of the heat island on cooling and heating needs. This includes population density and the average annual temperature of the local climate. The normal range maximum is given by a study done to measure the urban heat island effect in the warm climate of Los Angeles, which is then divided out by the total area of paved surfaces to obtain the increase in air conditioning electricity demand per .01 decrease in pavement albedo. The minimum is assumed to be zero, since the effect on reducing heating loads in cold climate cities has not been found to be studied in the literature.

Carbonation

Much of the carbon dioxide that was originally liberated from limestone in the cement production process rebinds to $Ca(OH)_2$ in the cement by what is known as carbonation. This effect is not applicable to asphalt pavements, and depends mostly on the compressive strength (and thus air penetration) of the concrete, as well as the average annual temperature in the ambient climate. Carbonation ranges from a low of 1.4% re-absorption for high-strength concrete buried under a sealing layer, to a high of 15% re-absorption for exposed low-strength concrete in a warm North American climate. The carbon dioxide is maximally absorbed by 75% of the $Ca(OH)_2$ in cement, and provides our extreme range maximum (Nielsen, 2007).

Lane Closure

Lane closure refers to the temporary closure of a roadway during maintenance and rehabilitation activities, which can cause increased traffic congestion and rerouting to longer routes, resulting in greater vehicle emissions. The emissions depend on many parameters specific to the site and project, especially traffic volume, project duration, and closure schedule. Studies that consider the upper range of the relevant parameters estimate lane closures to be responsible for the largest portion of emissions during the life cycle. A study that looked closely at many methodologies highlights the wide variability of emissions due to lane closures, and the difficulty of accurate calculation, but nonetheless estimate the normal and extreme range to be 1,000 tons and 10,000 tons of CO_2e for 1 lane-km during a 50 year pavement lifetime for both pavement types (Santero, 2009).

Lighting

Another effect on energy demand due to the color of pavements is surface lighting at night time. Lighting requirements are specified by National AASHTO recommendations, which have been adopted as requirements in some state Departments of Transportation (AASHTO, 2005). These recommendations vary according to two parameters: pavement classification by color and roadway classification (arterial or freeway).

The minimum lighting recommendations are given in lux, which measures the amount of visible light that hits a given surface. This varies from 6 lux, for concrete or asphalt with 15% artificially whitened aggregate on a freeway, to 17 lux on an asphalt arterial roadway. A relatively low efficiency, mercury vapor lamp is chosen to estimate a wider range of impact than a higher efficiency lamp would (Santero, 2009). Assuming an average illumination of 11 hours per day, the GHG emissions due to lighting vary from 109-309 Mg CO_2e during the 50 year lifespan (Santero, 2009). These values are doubled to estimate the maximum range, since the recommendations are a mere minimum.

Rolling Resistance

Rolling resistance refers to a decrease in fuel efficiency as contributed by the road surface. This is due to both the pavement structure and surface roughness.

Pavement structure can vary among the two major classes (flexible, rigid, and composite), and it can be misleading to characterize the issue as asphalt versus concrete because of this variability and because of composite layering (Santero, 2009). But in general, pavement structure has an effect that favors rigid (concrete) over flexible (asphalt) surfaces. One study estimates a fuel efficiency decrease of 20% for heavy vehicles on asphalt (Zaniewski, 1989). Since then, more careful studies have been done that estimate the increase in fuel consumption to be 2.9% for light vehicles and 6.9% for heavy vehicles (G.W. Taylor Consulting, 2002). These values depend heavily on vehicle speed and surface temperature, and merit more careful study that potentially includes effects of urban density and climate. Here we take 2.9% and 6.9% as the upper limit increase for the normal range in fuel consumption on asphalt pavements, with traffic volumes of 6,000 trucks per day and 24,000 light vehicles. The extreme range assumes Zaniewski's 20% fuel consumption increase for heavy vehicles.

Surface roughness is an effect of wear accumulated on the road surface that increases fuel consumption of vehicles. This includes both unevenness of the road, and megatexture, as the finer textures (macrotexture and microtexture) are agreed to have little effect on fuel consumption (Santero, 2009). Because of different test vehicles and pavement conditions, there is not close agreement about the effect of surface roughness in the literature, and the values range from about 2-12% increase in fuel consumption when comparing a "rough" to a "smooth" surface (Santero, 2009). We assume the midpoint of 7% for the maximum value of the normal range for both pavement types, and 12% for the extreme range. This difference due to this effect between asphalt and concrete pavements is not well established in the literature, and so is attributed equally to both types.

End of Life

Recycling is commonly practiced for asphalt pavements, and can be done off site, or the asphalt overlay can be heated for removal and processed on site and partially substitute for virgin mix. About 80% of asphalt is recycled at the end of life, 90% of which goes to pavement applications (Horvath A. , 2003). State DOTs place limits on the amount of Reclaimed Asphalt Pavement that can go into overlay, ranging from 0%-70%, and unregulated in some states (Banasiak, 1996). The different methods include remix at a central plant, hot in place and cold in place recycling, and have variable energy and materials use. Hot in place recycling requires addition of a recycling agent in a 6% proportion, while cold in place recycling requires addition of up to 2% bitumen emulsion. Since data on these additives is poor, practices vary so significantly, and because of the complex effects recycling has on design, recycling is not accounted for in the general results, but presented separately.

The end of life of concrete is not as neatly self-contained as the above recycling process. The most climate-friendly option is using waste concrete as recycled aggregate for subbase applications. An average of 34% of all concrete ends up recycled as subbase, and 3% as aggregate for new cement concrete (Horvath A. , 2003). Steel reinforcement is also recycled, in 2008 70% of it was recovered at the end of life for recycling (U.S. Geological Survey, 2010).

Final disposal at the end of the 50 year period is attributed no emissions.

Results and Discussion

In order to determine the sensitivity of the results of the pavement life cycle model to the various parameters that those results depend on, a series of scenarios are run that isolate life cycle components and the parameters that that component depends on. The parameters that affect the life cycle component of concern are varied across the "normal" and "extreme" range values, and the results are recorded for that life cycle component. An example is the life cycle component of rolling resistance, which is strictly dependent on the parameters of overlay type (asphalt or concrete), traffic volume of trucks and of light vehicles, and increase in fuel consumption for trucks and for light vehicles on that overlay type. Those parameters which do not affect the component under consideration are set to the average value. With a range of values given for each of these parameters, in both the normal and extreme cases, a corresponding range for the GHG emissions due to rolling resistance is calculated. Many parameters affect multiple life cycle components, such as traffic's effect on rolling resistance and on maintenance, and thereby have a compound effect on the total life cycle emissions. Below is a table that summarizes the life cycle components and the parameters that they depend on.

Life cycle component	Parameters	Life cycle component	Parameters
Aggregate, Base, and Rebar Materials and Mix Production	Overlay and Base Depth/Density Overlay and Base Composition (Design depends on loading, traffic volume, climate, State DOT specs) Aggregate extraction crushing energy Rebar volume and recycled content Maintenance/recycling practices	Carbonation	Pavement type / Porosity Climate
Binder (Cement/Bitumen) Production	Overlay Depth/Density Overlay Composition Facility efficiency Fly ash substitution Maintenance/recycling practices	Lane Closures	Traffic Maintenance Type Pavement Setting Duration
Construction	Aggregate drying energy Onsite equipment emissions	Lighting	Pavement Albedo Road type (Highway/arterial)
Transportation	Distance Mode Import/Domestic Maintenance and recycling practices	Rolling Resistance	Traffic composition Traffic volume Vehicle base fuel efficiency Pavement Type
Albedo	Pavement Albedo	End of Life Options	Pavement type Recycling type Addition of virgin mix Recycling Agent addition Bitumen Emulsion addition

Once a range is determined for emissions totals due to each life cycle component, these are summed at the level of the primary life cycle phases as well as the total life cycle. Varying all relevant parameters as described allows us to see how widely variable the range of practices is, but the same process also allows analysis of the sensitivity only to specific parameters. The results below give a general range of life cycle greenhouse gas emissions for both pavement types by varying all parameters except for maintenance schedules and recycling practices, the sensitivity of which is analyzed separately because of their heavy influence on almost every life cycle phase.

General Sensitivity Analysis

Figure 1 below shows the range of life cycle greenhouse gas emissions when all of the included parameters are varied (except for maintenance schedules and recycling practices), given in kg CO_2e per square meter of pavement surface.

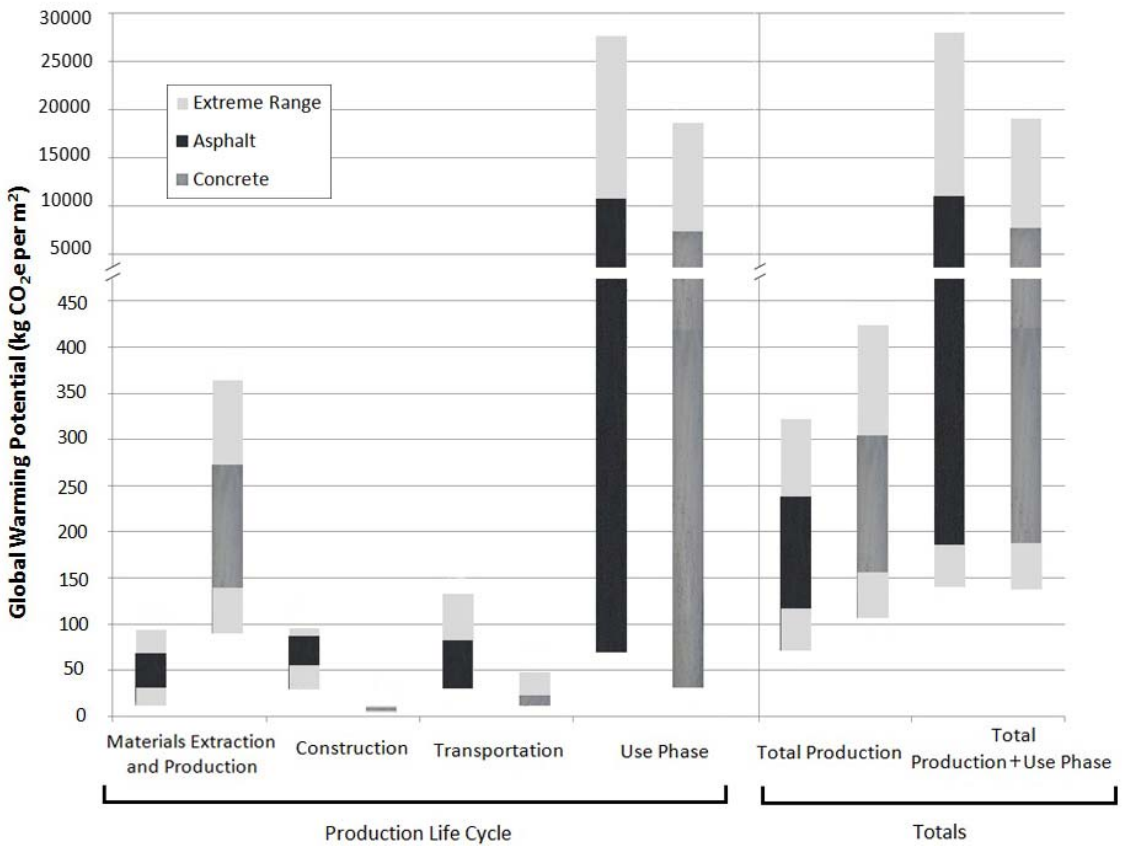

Figure 1 - Greenhouse gas emissions ranges for each life cycle phase for asphalt and concrete pavements.

On the left side of the graph are the contributions from each life cycle phase, and on the right are the totals, shown with and without the use phase. There is a break in the vertical axis of the graph between 450 and 5000 kg, and the scale of the vertical axis above the break is different from the scale below the break. This is to include the use phase, which has the largest potential contribution to a given pavement as well as the widest range of emissions contributed.

During the production life cycle, there is large variability during the "Materials Extraction and Production Phase," which normally varies by about a factor of two for both asphalt and concrete, and for the extreme range by a factor of four for concrete, and a factor of almost eight for asphalt. This range is mostly sensitive to the thickness of the overlay, base and subbase layers, which also affects the construction and transportation phases. There is also a considerable range in transportation emissions, especially in the extreme where all aggregate is imported, bitumen comes from Venezuela and cement comes from Spain.

The immense and widely variable impact of the use phase is primarily due to rolling resistance, which has an enormous impact on the life cycle emissions for some pavements, and very little impact on others, and depends primarily on traffic volume. The components of the use phase are drawn out separately in Figure 2. Rolling resistance has a greater effect for asphalt than for concrete, because of the flexible structural nature of asphalt. Rolling resistance on concrete also contributes an order of magnitude greater emissions than the combined production phases, due to the roughness of the pavement surface. This effect is larger than the pavement structure, and the maximum roughness is assumed equal for both pavement types. Lane closure is the next largest component in the use phase, especially in the extreme, which represents the potential of poorly managed construction activities to contribute heavily to GHG emissions.

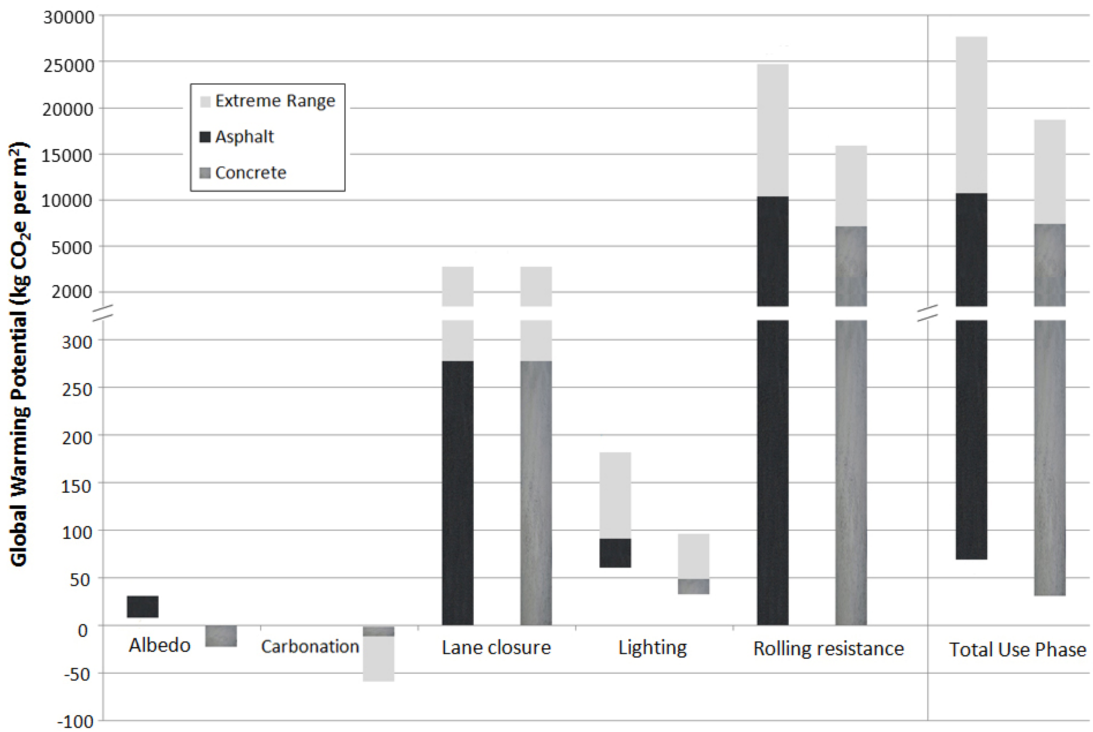

Figure 2 - Greenhouse gas emission ranges for each use phase component for asphalt and concrete pavements.

Sensitivity to Maintenance Schedules

Since maintenance and rehabilitation practices affect the materials and energy needs during all production life cycle phases, and because of the wide variability in practices, the effect of this parameter is analyzed in isolation. Based on the maintenance schedules outlined above, during the 50 year lifetime, the normal range for asphalt is between 3.12 and 3.84 rehabilitations, and between 2.5 and 7.14 in the extreme range. For concrete, the normal range is 1.75 to 2.17 rehabilitations, and the extreme 1 to 2.85.

With the exception of lane closures, the use phase is not affected by maintenance schedules, hence this portion is drawn from the results above. The correlation between maintenance and lane closures has not been established in prior studies, nor is a relationship modeled here. All other parameters are set to average values.

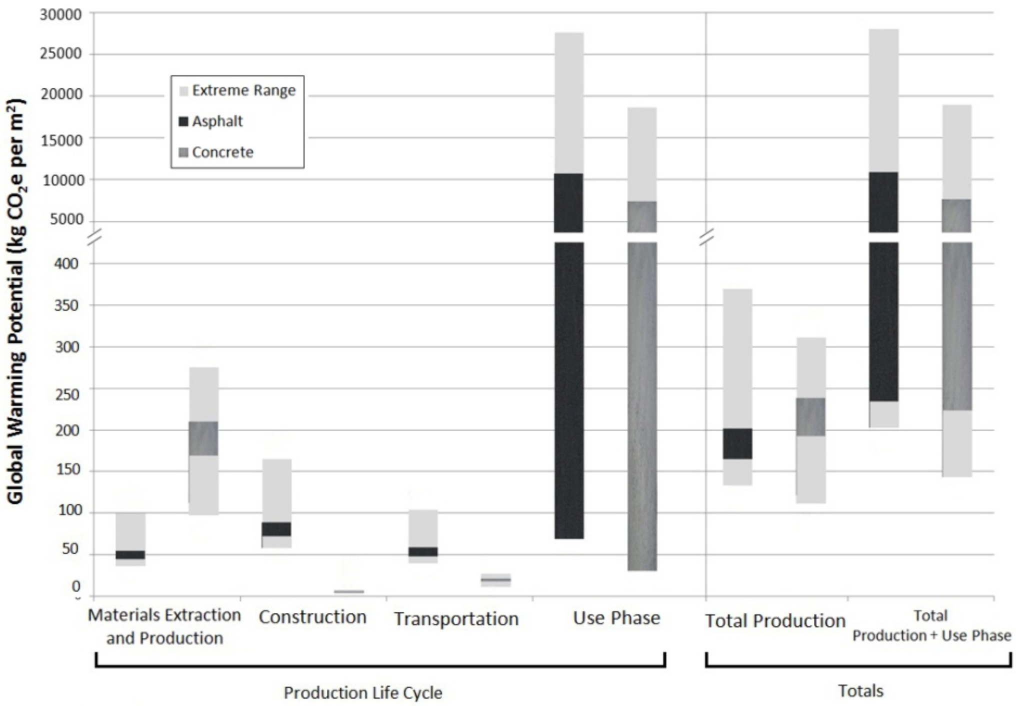

Figure 3 – Sensitivity to maintenance schedules: Greenhouse gas emissions ranges for each life cycle phase contribution for asphalt and concrete pavements.

The results for the production life cycle are sensitive to maintenance in a positively linear fashion for all phases. Values of the normal range are based on Gharaibeh & Darter, which shows how maintenance schedules vary with traffic volume in Illinois; whereas the maximum range used is based on several studies, hence there is much more variance in the maximum range. This lends the conclusion that the GHG impact of equivalently engineered asphalt and concrete pavements during the production life cycle is case dependent. We can imagine a region where different maintenance practices are employed for the two pavement types as compared to Illinois, depending on climate effects, state DOT regulations, traffic, etc.

Sensitivity to Recycling Practices

Recycling also affects many of the life cycle phases through substitution of materials and reliance on entirely different production infrastructure. The data are also less certain at this stage with regard to recycling energy and life cycle inventories of necessary additives such as recycling agents and bitumen emulsions. So as not to compromise the primary results for virgin production, recycling is analyzed separately. Recycled concrete that enters back into ready mix production requires crushing much like virgin aggregate, so the resulting life cycle emissions are identical if the same assumptions are made for aggregate crushing energy, transportation distance, and cement-to-aggregate ratio. The results for recycled asphalt, however, are shown below.

All parameters (except maintenance schedules) are varied just as with the general result, and it assumes 50% hot in place recycling, and 50% cold in place recycling. The "recycling" phase accounts for on site activities for in situ recycling, as well as production of recycling agent and bitumen emulsion additives.

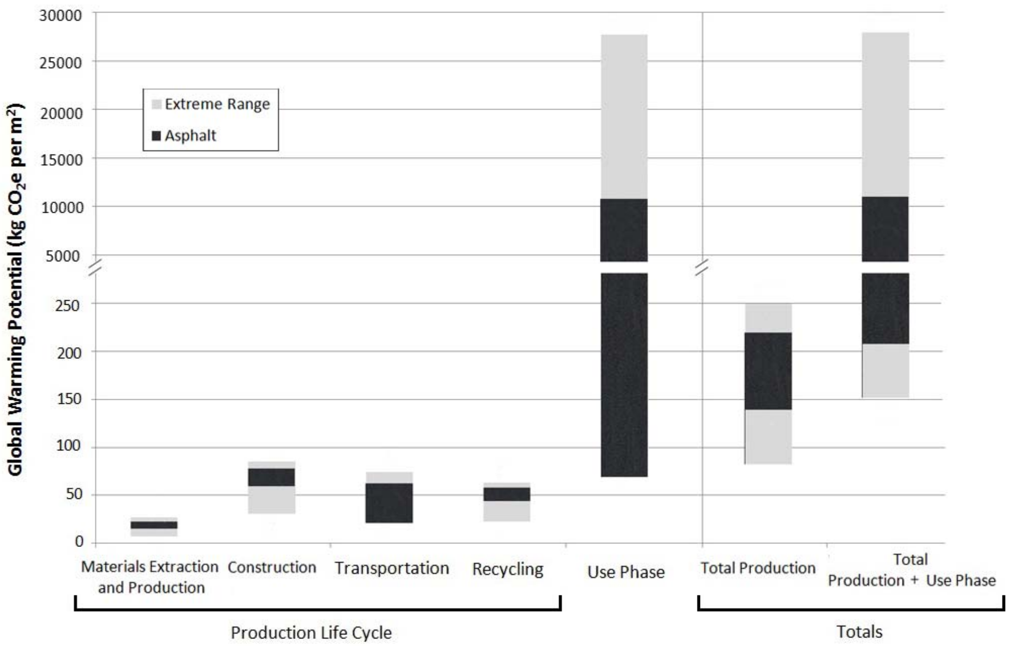

Figure 4 – Sensitivity to recycling practices: Greenhouse gas emissions ranges for each life cycle phase contribution for asphalt and concrete pavements.

Final Remarks

The above results lend the conclusion that environmental policy adoption and future research should prioritize two areas that by far contribute more than other factors in the life cycle of pavements: rolling resistance and maintenance practices. The effect of rolling resistance is not in agreement in the currently available studies, nor are the isolated effects of pavement structure and pavement roughness on both pavement types understood. Similar uncertainty holds for maintenance and lane closure delays: "although accurately forecasting future maintenance activities (including rehabilitation) continues to be a challenging task within the pavement engineering profession, the level of sophistication extends far beyond the current LCA framework" (Masanet, Santero, & Horvath, 2010).

Other areas for data quality improvement are: heat island effect in cold climates; LCI data on additives, admixtures, recycling agents, and bitumen emulsions; and onsite equipment emissions data for site clearance, pavement removal, and in place recycling. The effect of carbonation during landfill is not taken into account, which if crushed and sufficiently exposed to air could absorb significant quantities of carbon dioxide.

By examining a minimum and maximum range in the analysis, the study has not taken into account intermediate values, such as preventive maintenance procedures, which would allow analysis of context-dependent scenarios and thereby allow engineers and policy makers to make environmentally oriented decisions.

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