Greenhouse Gas Emissions Reduction Opportunities for Concrete Pavements

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Summary

Concrete pavements are a vital part of the transportation infrastructure, comprising nearly 25% of the interstate network in the United States. With transportation authorities and industry organizations increasingly seeking out methods to reduce their carbon footprint, there is a need to identify and quantitatively evaluate the greenhouse gas (GHG) emission reduction opportunities that exist in the concrete pavement life cycle. A select few of these opportunities are explored in this article in order to represent possible reduction approaches and their associated cost-effectiveness: reducing embodied emissions by increasing fly ash content and by avoiding overdesign; increasing albedo by using white aggregates; increasing carbonation by temporarily stockpiling recycled concrete aggregates; and reducing vehicle fuel consumption by adding an extra rehabilitation. These reduction strategies are evaluated for interstate, arterial, collector, and local road designs under urban and rural scenarios. The results indicate that significant GHG emission reductions are possible, with over half of the scenarios resulting in 10% reductions, compared to unimproved baseline designs. Given the right conditions, each scenario has the potential to reduce GHG emissions at costs comparable to the current price of carbon.

Introduction

The construction, operation, and maintenance of the U.S. roadway system are responsible for substantial energy and resource consumption. Although the cumulative environmental impact of the road network is unknown, there is reason to believe that significant greenhouse gases (GHGs) are released during the construction and operation of pavements. According the United States Geological Survey (USGS), 460 million metric tons of crushed aggregate alone go into the construction, rehabilitation, and maintenance of the U.S. pavement network (USGS 2011) in order to provide service for over 5 trillion vehicle-kilometers per year (USDOT 2011).[1] Passenger and freight movement on roadways accounts for 83% of carbon dioxide (CO_2) emissions from the transportation sector and 27% of total CO_2 emissions in the United States (EPA 2009). Although the bulk of the these road transport emissions should not be attributed to the pavements themselves, the materials and serviceability levels required of this infrastructure system give rise to a notable GHG emission source.

Reducing the GHG emissions of pavements requires a complete understanding of how it impacts the natural environment. Like any other product or service, pavements generate GHG emissions throughout their service life, beginning with raw materials extraction and manufacturing, continuing through construction, operation, and maintenance, and, finally, ending with waste management and recycling. Life cycle assessment (LCA) is designed to capture each of these phases in order to create a portrayal of the sources and magnitude of emissions over the life cycle. This approach not only quantifies the current footprint, but also is useful in identifying and quantifying potential opportunities to reduce those impacts.

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This article focuses on GHG reduction opportunities for concrete pavements, as measured by their global warming potential (GWP). Emissions are quantified for a select number of strategies, then evaluated for their cost-effectiveness using life cycle cost analysis (LCCA) principles. The strategies are developed and applied to representative designs for each Federal Highway Administration (FHWA) roadway classification in the United States, spanning from rural local roads to urban interstates. The results demonstrate a set of opportunities and economic impacts that Departments of Transportation (DOTs) and other stakeholders can use to decrease the GHG emissions of their roadway networks.

Opportunities for Greenhouse Gas Emission Reductions

Concrete pavements offer an abundance of opportunities for GHG reductions. Four broad approaches are explored in this article: reducing embodied emissions; increasing albedo; increasing carbonation; and reducing vehicle fuel consumption. Most strategies can be grouped into one of these approaches, making this a convenient organizational method in which to characterize potential improvement opportunities.

Embodied emissions are those released during the manufacturing and construction of paving materials. Essentially, these are the emissions embodied in the pavement when it begins its service life, as well as those materials that are added during maintenance operations. These emissions can be reduced by using fewer natural resources, substituting less emission-intensive materials, or increasing production efficiency.

Albedo measures the fraction of incoming solar radiation that is reflected by the pavement surface. Increasing albedo reduces the climate impacts from both the urban heat island effect and direct radiative forcing. Albedo also correlates with lighting demand, thus affecting the electricity needed to illuminate a roadway. Concrete naturally enjoys a relatively high albedo, but improvements can be made to the concrete mix that increase the albedo even further, such as the use of white aggregates, white cement, and slag.

Carbonation is a chemical process by which CO_2 is naturally sequestered in the concrete. Carbonation for an in-situ concrete pavement is usually minimal, penetrating only a few centimeters into the pavement over its service life and thus sequestering only a fraction of the CO_2 release during calcination. Following Fick's law of diffusion, carbonation is expedited with increases in the surface-area/volume ratio—something that occurs when concrete pavements are crushed at the end of their service life. Crushed concrete is typically recycled as base, fill, or concrete aggregates, which all present an opportunity for carbon sequestration.

Vehicle fuel consumption is affected by the choice in pavement design, maintenance, and materials. Most vehicle fuel consumption is unaffected by pavement-related issues, but GHG emissions from increased vehicle fuel consumption resulting from pavement-vehicle interaction (e.g., increased roughness or reduced stiffness) and traffic delay (caused by pavement construction activities) can be significant and should be allocated to the pavement life cycle (Santero and Horvath 2009). With upward of 100,000 vehicles per day traveling over certain structures, pavement characteristics that offer even slight fuel economy improvements can significantly decrease the GHG emissions associated with the pavement life cycle.

The Role of Economics

Economics provide the critical link that helps implement environmental impact reduction strategies into DOT decision-making frameworks. Although most DOTs and other stakeholders are interested in reducing GHG emissions, the primary goal remains to provide maximum pavement performance within budgetary constraints. Reaching environmental targets necessarily becomes a secondary priority. In order to effectively integrate GHG reduction strategies into DOT decision making, it is essential to appreciate that reductions must be achieved at minimal costs.

LCCA offers a method of analyzing the economic impacts of pavements and is often used at DOTs for deciding between design alternatives. LCCA can also be used to determine the cost-effectiveness of environmental improvement strategies—the application used in this research. Coupling LCCA with LCA provides a holistic view of both the economic and environmental impacts of a given strategy, thus providing decision makers with a more complete set of information.

Methodology

The baseline designs and reduction scenarios are evaluated using a pavement LCA model developed at the Massachusetts Institute of Technology (MIT) Concrete Sustainability Hub. The model captures impacts from each phase of the pavement life cycle: materials; construction; use; maintenance; and end of life (EOL). The model is built primarily in the *GaBi* LCA software package, with external data (e.g., albedo impacts and carbonation rates) and models (e.g., traffic delay models and pavements design models) supplemented as necessary. More information about the MIT model and its workings are available in work by Santero and colleagues (2011) and Loijos (2011).

Baseline Designs and Emissions

Baseline designs are created and evaluated for 12 functional units, which collectively characterize each roadway classification in the United States. The functional units are based on centerline-kilometers (cl-km), rather than lane-kilometers (lkm), in order to capture the impacts of a typical structure as a whole, including both the mainline and shoulders. Estimates for the more traditional lkm metric can be back-calculated using the given data. Geometric and traffic data are taken from *Highway Statistics 2008* (FHWA 2008); accompanying pavement structures are designed using the American Association of State Highway Officials (AASHTO) method for rigid

Table 1 Baseline pavement designs and global warming potential

Roadway classification		*Traffic (AADT/AADTT)*	*Total lanes*	*Paved width (m)*[a]	*Concrete thickness (mm)*	*Base thickness (mm)*	*Estimated GWP (Mg CO_2-eq/cl-km)*[c]
Rural	Interstate	22,000/4,400	4	23	292	152	3,800
	Principal arterial	6,400/710	2	12	203	152	1,300
	Minor arterial	3,100/310	2	12	191	152	1,200
	Major collector	1,200/85	2	10	152	152	770
	Minor collector	570/40	2	10	127[b]	0	540
	Local	180/12	2	8	102[b]	0	340
Urban	Interstate	79,000/6,300	6	34	305	152	6,700
	Freeway	54,000/2,200	4	23	279	152	2,400
	Principal arterial	20,000/790	4	20	216	152	2,100
	Minor arterial	9,700/3,980	2	12	178	152	1,400
	Collector	4,200/170	2	12	165	0	960
	Local	980/39	2	10	127[b]	0	610

[a] Includes mainline and shoulders.

[b] These pavements may be thinner than some states allow. However, the 1993 AASHTO design procedure was still followed to remain consistent.

[c] Results from Santero and colleagues (2011)

Note: AADT = annual daily traffic; AADTT = annual daily truck traffic; GWP = global warming potential; cl-km = centerline-kilometer; one meter (m, SI) $\approx$ 3.28 feet (ft); one millimeter (mm) = 10^{-3} meters (m, SI) $\approx$ 0.039 inches; carbon dioxide equivalent (CO_2-eq) is a measure for describing the climate-forcing strength of a quantity of greenhouse gases using the functionally equivalent amount of carbon dioxide as the reference. One megagram (Mg) = 1 metric ton (t) = 10^3 kilograms (kg, SI) $\approx$ 1.102 short tons.

pavements (AASHTO 1993, 2004). The concrete mix has a flexural strength of 4.5 megapascals and uses 335 kilograms per cubic meter of cementitious material (90% portland cement and 10% coal fly ash).[2] It is important to note that the 10% fly ash is a gross average for use in a concrete pavement (ACAA 2009; USGS 2009), but is not necessarily a typical replacement rate for concrete mixes because of potentially poor resistance to alkali silica reaction.

A 40-year analysis period is used for the baseline designs, which includes rehabilitation activities at years 20 and 30 consisting of slab replacement (4%) and diamond grinding. Note that the 40-year analysis period is an assumption, and that concrete pavement service lives will, in practice, vary widely. The analysis period and rehabilitation schedules and activities are based on surveys of state DOTs with respect to their LCCA procedures (Rangaraju et al. 2008; Minnesota Department of Transportation 2007).

Table 1 shows the relevant designs inputs and estimated life cycle GWPs as determined by the MIT pavement LCA model. Table S1 in the supporting information available on the Journal's Web site contains mass and other relevant data. More complete descriptions of the baseline designs and the calculation of the life cycle GWP values are found in work by Santero and colleagues (2011).

Greenhouse Gas Emission Reduction Strategies

Five GHG reduction strategy strategies are explored, with at least one strategy from each of the categories presented in the introduction: (1) reducing embodied emissions through increased fly ash replacement of cement; (2) increasing albedo using white aggregates; (3) increasing carbonation through EOL waste concrete management; (4) reducing fuel consumption by adding an extra rehabilitation activity; and (5) reducing embodied emissions by avoiding overdesign through the use of advanced design models. A summary of strategies and the notable differences between the baseline scenarios are given in table 2. The relevant inventory emission data are given in table 3.

Of note is that the chosen strategies are not meant to be an exhaustive set of options for reducing GHG emissions, but rather an exploratory set of opportunities. Also of note is that these reductions are based on average roadway dimensions and structures, thus lacking the project-specific inputs that are necessary to obtain context-specific results. The intent is to provide estimates for a select number of generalized strategies in order to gain insight into the magnitude of possible GHG reductions.

1. Fly ash is already widely used in the concrete industry as a supplementary cementitious material (SCM). An increase from 10% (the average fly ash used in concrete pavement mixes) to 30% fly ash replacement is modeled here to exemplify the possible reduction from one embodied emissions reduction strategy. The 30% replacement of cement with fly ash is based on a survey of DOT practices (ACPA 2011), but is admittedly a conservative ceiling. An added benefit of higher fly ash contents is expedited carbonation: Mixes with 10% and 30% replacement have been shown experimentally to increase the carbonation coefficient (i.e., the rate of carbonation) by approximately 5% and 10%, respectively (Lagerblad 2006).
2. White aggregates (both fine and coarse) are used in pavement design to increase the pavement albedo. Increased

Table 2 Summary of key differences between baseline and GHG reduction scenarios

Strategy	*Description*	*Baseline scenario*	*GHG Reduction scenario*
1. Increasing fly ash	Increased usage of fly ash to replace portland cement	10% fly ash replacement	30% fly ash replacement
2. White aggregate	Switch to high-albedo fine and coarse aggregates	$\alpha_{\text{concrete}} = 0.33$	$\alpha_{\text{concrete}} = 0.41$
3. EOL stockpiling	Crush and expose recycled concrete to expedite carbonation	0% EOL carbonation	28% EOL carbonation
4. Extra rehabilitation	Grind at year 10 to reduce pavement roughness	See table S3 on the Web	See table S3 on the Web
5. Avoiding overdesign	Reduce material demand by using a mechanistic-empirical design approach	See table S3 on the Web	See table S3 on the Web

Note: GHG = greenhouse gas; EOL = end of life.

Table 3 Inventory data for significant materials and processes relevant to the reduction scenarios

	GWP emissions factor	*Source*
Cement	0.93 kg CO_2-eq/kg	Marceau and colleagues (2006)
Fly ash	0.01 kg CO_2-eq/kg	PE International (2011)
Water	0.005 kg CO_2-eq/kg	PE International (2011)
Aggregate	0.0032 kg CO_2-eq/kg	Zapata and Gambatese (2005)[a]
Diesel[b]	3.2 kg CO_2-eq/L	PE International (2011)
Gasoline[b]	2.6 kg CO_2-eq/L	PE International (2011)
Truck transport	0.089 kg CO_2-eq/Mg-km	PE International (2011)
Pavement roughness	Cars: 0.01 L/km per 1 m/km increase in IRI Trucks: 0.04 L/km per 1 m/km increase in IRI	Zaabar and Chatti (2010)[a]
Diamond grinding	1,600 L diesel/lkm	IGGA (2009)
Radiative forcing	2.6 kg CO_2-eq/m^2 per 0.01 decrease	Akbari and colleagues (2009)
Urban heat island	4.9 g CO_2-eq/m^2 per 0.01 decrease in albedo	Rosenfeld and colleagues (1998)
Lighting	0.040 kWh/lumen/yr	AASHTO (2005)[a]
Electricity (input)	0.79 kg CO_2-eq/kWh	PE International (2011)
In-situ carbonation	1.58 mm/$y^{0.5}$ (1.65 mm/$y^{0.5}$ for 30% fly ash)	Lagerblad (2006)

[a] CO_2-eq emission factor value was derived based on data reported in the given source.

[b] includes upstream and combustion emissions.

Note: IRI = international roughness index; kg CO_2-eq/kg = kilograms carbon dioxide equivalent per kilogram; CO_2-eq/L = carbon dioxide equivalent per liter; CO_2-eq/Mg-km = carbon dioxide equivalent per megagrams per kilometer; m/km = meters per kilometer; lkm = lane-kilometers; mm/$y^{0.5}$ = millimeters per square root of years. One liter (L) = 0.001 cubic meters (m^3, SI) ≈ 0.264 gallons (gal); one square meter (m^2, SI) ≈ 10.76 square feet (ft^2); one kilowatt-hour (kWh) ≈ 3.6×10^6 joules (J, SI) ≈ 3.412×10^3 British Thermal Units (BTU).

albedo increases the reflectivity of the pavement surface, allowing for reduced lighting demand, decreased urban heat island effect, and increased radiative forcing. The average albedo of the baseline concrete pavement is taken to be 0.33; the white aggregate pavement has an albedo of 0.41 (Levinson and Akbari 2002). Tables S1 and S2 in the supporting information on the Web contain information on the estimated lighting demands for the various roadway classifications.

3. EOL stockpiling consists of crushing and stockpiling the concrete for 1 year, during which time it was assumed to sequester 28% of the initial CO_2 released from carbonation, or 155 grams of CO_2 per kilogram of cement in the mix (Dodoo et al. 2009). It should be noted that actual carbonation is difficult to pinpoint and that the empirical data used for this estimate should be refined as more precise models become available. There are also practicality issues to consider, such as the willingness of DOTs and/or industry to stockpile recycled concrete for months at a time. This strategy represents only one option available at the EOL, although other options are likely similar in terms of the magnitude of emission reductions.
4. Adding an extra rehabilitation at year 10 reduces vehicle fuel consumption by creating a smoother ride. Zaabar and Chaati (2010) estimate that a decrease in roughness of 4 meters per kilometer (m/km) reduces fuel consumption by 4.2% for cars and 2.8% for trucks. The extra rehabilitation itself consumes additional energy from diamond grinding and requires that the structure is 1 centimeter thicker at the initial construction in order to account for the material that will be removed during the grinding. The additional activity benefits the life cycle in two ways: First, the pavement roughness is brought back down to an initial international roughness index (IRI) of 1.0 m/km;

second, completely uncarbonated concrete is exposed to the environment and carbonation resumes again at its faster, initial rate. The average IRI values for years 10 through 20 are given in table S3 in the supporting information on the Web for both the baseline and reduction scenarios.

5. Avoiding overdesign decreases embodied emissions by optimizing the materials necessary to construct the pavement structure. Long-term pavement performance data collected by the FHWA suggest that concrete pavements routinely supported up to ten times the traffic that they were designed to carry (CEMEX 2010). In order to evaluate the GWP of the more accurate designs, the Mechanistic-Empirical Pavement Design Guide (MEPDG) models was used to create alternative designs using equivalent traffic and service life inputs, assuming moderate climate conditions. The structure designs for six of the twelve roadway classifications are listed in Table S3 in the supporting information on the Web, as compared to their 1993 AASHTO equivalents. MEPDG is primarily a high-traffic volume design tool and does not provide outputs of less than 178 millimeters for the concrete slab thickness, so the low-volume classifications are not analyzed.

Cost-Effectiveness Analysis

Cost-effectiveness analysis (CEA) is most commonly associated with the health and medicine fields, where it is used to evaluate the cost of different interventions with respect to their ability to increase quality of life (Gold 1996). Applying the concept to pavements and GHG emissions, reduction strategies can be evaluated not only on their reduction potential, but also on the relative cost of that reduction. Thus, cost-effectiveness in this study speaks to the cost to reduce GHG emissions, measured in U.S. dollars per megagrams of CO_2 equivalent (\$/Mg CO_2-eq).[3] Equation 1 provides the basic relationship between costs, emissions, and cost-effectiveness (CE). The "alt" and "base" subscripts refer to the reduction alternative and baseline case, respectively.

$$CE_{alt} = \frac{cost_{alt} - cost_{base}}{emmissions_{alt} - emissions_{base}} = \frac{\Delta cost_{alt-base}}{\Delta emissions_{alt-base}} \qquad (1)$$

The outputs of the GWP reduction analysis determine the values for the denominator of equation (1); the numerator is determined through economic analysis. Following established LCCA protocols, the absolute cost of each strategy is not necessary to compute if the difference between the base and reduction strategy cases is known. Because many cost inputs will be identical between alternatives (e.g., construction processes, mobilization, and unit costs), the demand for data is significantly reduced. Practitioners can focus on the differences between designs rather than calculating comprehensive, but largely irrelevant, absolute costs. Sensitivity analyses are performed for selected parameters in order to estimate a range of expected costs. Table 3 summarizes the cost and other data used in the CEA.

This analysis uses a transportation agency perspective on cost abatement, thus adopting the LCCA approach that DOTs currently use in their decision-making process. In general, the FHWA (Walls and Smith 1998) recommends using the discount rate published in the most current version of the White House Office of Management and Budget (OMB) Circular A-94; accordingly, this analysis discounts future costs at a rate of 2.3% (OMB 2010). It should be noted that many abatements analyses, such as McKinsey & Company (Creyts et al. 2007), use levelized costs, particularly in the field of energy improvements where the concept was first established (Meier 1984). This approach annualizes the economic impact over the life of the reduction strategy. In order to equitably compare the results in this CEA with other abatement curves, it may be necessary to convert the results to levelized costs using the data already provided.

Results

Greenhouse Gas Emission Reductions and Costs

The reductions in GWP for each scenario are shown in figure 1. The absolute values show quantity of GWP reduced. Higher-volume roadways, such as urban interstates, have larger absolute reduction potentials because of the larger structures and from roughness-related vehicle fuel consumption. Accordingly, reducing embodied emissions (through increased fly ash or avoided overdesign) and reducing smoothness (through an extra rehabilitation) have the largest reductions for interstates.

Although lower-volume roadways have smaller absolute reduction potentials, the reductions relative to their baseline scenarios are significant. Local roads contribute roughly ten times less life cycle GWP than their interstate counterparts, so even small reductions can have a large influence on the overall footprint. In particular, increasing albedo (through white aggregates) results in high relative reductions for local roads and collectors, with the strategy reducing GWP by 20% for these scenarios.

The cost-effectiveness of the GHG reduction strategies are shown in figure 2. The solid bars represent the results using the best-estimate data shown in table 4; the error bars represent the sensitivity to the low- and high-estimate data. Note that for clarity purposes, the y-axis stops at \$250/Mg CO_2-eq saved, even though some points are above that threshold. Strategies at that cost magnitude are significantly higher than estimated carbon prices and are thus considered to be above reasonable cost-effectiveness limits.

Each scenario for both of the embodied emissions strategies has a negative cost-effectiveness value, meaning that the strategies reduce both costs and emissions. Avoiding overdesign essentially reduces the thicknesses of the concrete and/or base layers, thus mitigating the costs and emissions associated with extraction, production, and handling of natural resources.

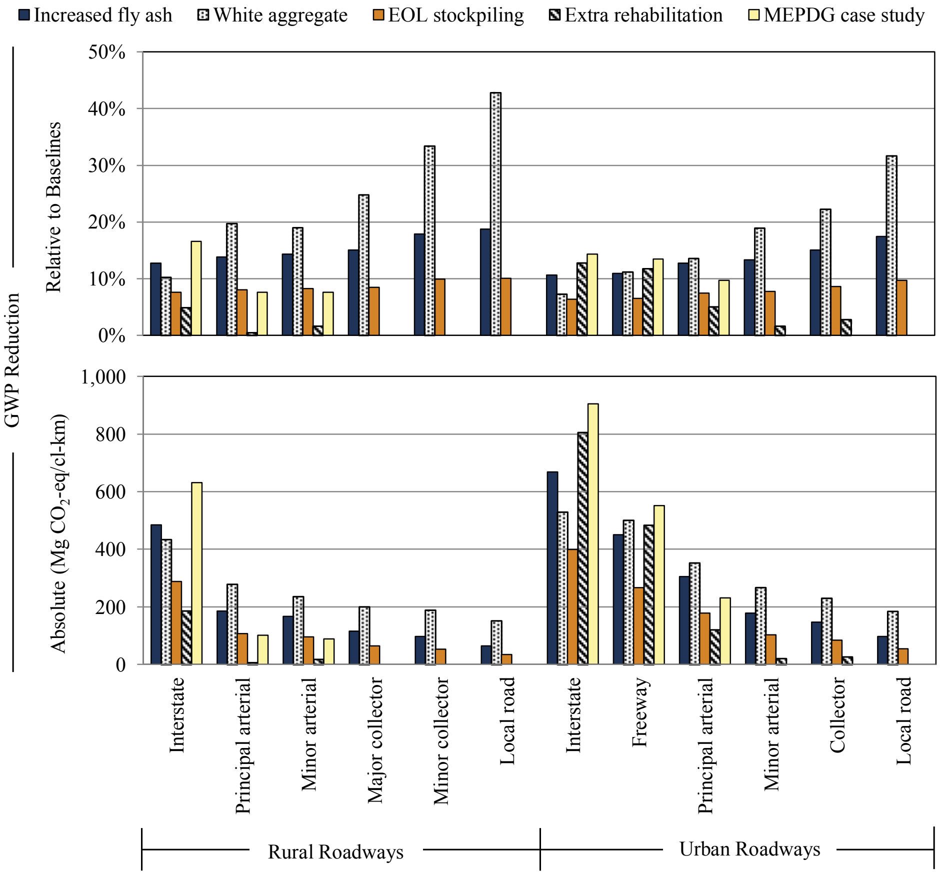

Figure 1 Life cycle GWP reductions shown in terms of absolute emission reductions (bottom) and relative reductions compared to the baselines (top). EOL = end of life; MEPDG = Mechanistic-Empirical Pavement Design Guide; GWP = global warming potential; Mg CO_2-eq/cl-km = megagrams carbon dioxide-equivalent per centerline-kilometer.

Table 4 Costs and other data used to conduct the CEA for the GHG emission reduction strategies

Parameter	*Best estimate*	*Low estimate*	*High estimate*	*Source*
Cement (\$/Mg)	\$102	—	—	USGS (2009)
Fly ash (\$/Mg)	\$50	\$25	\$65	Tikalsky and colleagues (2011)
Truck transport (\$/Mg-km)	\$0.10	—	—	Assumed
Extra aggregate haul (km)	50	0	200	Assumed
Recycled concrete value (\$/Mg)	\$7.43	—	—	USGS (2008)
Annual carrying cost (%/Mg/yr)	25%	20%	40%	Hendrickson (2008)
Grinding cost (\$/m^2)	\$4.31	\$4.00	\$5.00	Caltrans (2011)
Concrete pavement (\$/m^3)	\$212	\$151	\$273	Caltrans (2011)
Aggregate base (\$/m^3)	\$83	\$51	\$114	Caltrans (2011)

Note: \$/Mg = U.S. dollars per megagram; \$/Mg-km = dollar per megagram per kilometer; km = kilometer; %/Mg/yr = percent per megagram per year; \$/m^2 = dollars per square meter; \$/m^3 = dollars per cubic meter.

Increasing the fly ash content has negative cost-effectiveness values for the same reason, although the magnitude is considerably lower because the cost reductions are limited to the binding agent, rather than the structure as a whole.

The strategies to increase albedo, increase EOL carbonation, and reduce vehicle fuel consumption result in positive cost-effectiveness values. Following the trend from the emission reductions results, the use of white aggregates is more cost-effective on low-volume pavements, whereas the extra rehabilitation is more cost-effective on high-volume roadways. The cost-effectiveness of increasing carbonation through EOL stockpiling is consistent across all the classifications.

Figure 3 combines the absolute GWP reduction and the associated cost-effectiveness for the urban interstate and rural local road scenarios. The plot exemplifies the differences that exist between different roadway classifications. For instance, the

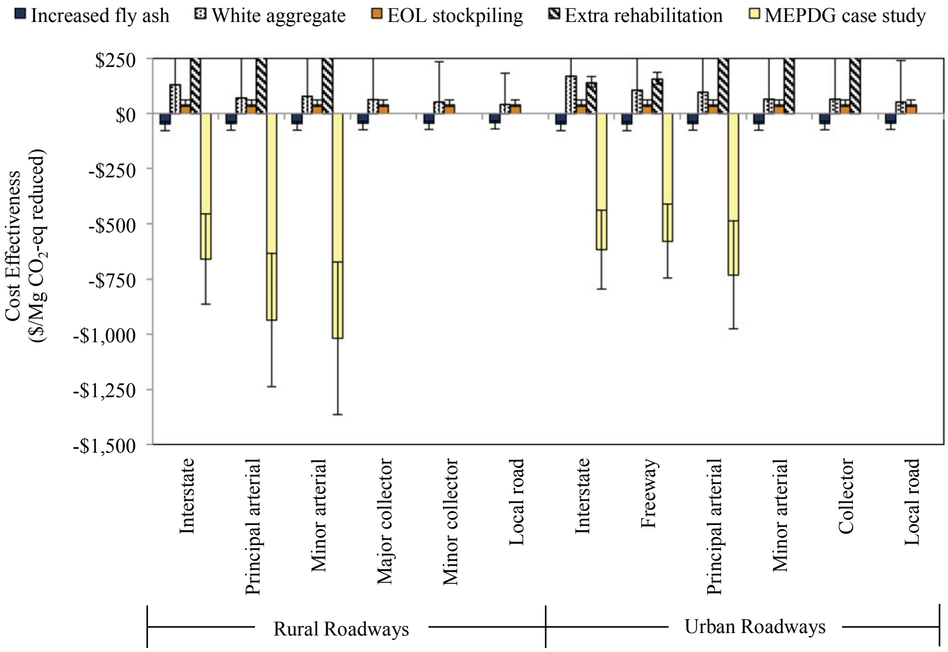

Figure 2 Cost-effectiveness of five greenhouse gas reduction strategies (solid bars represent best-estimate data, and error bars represent low and high data).

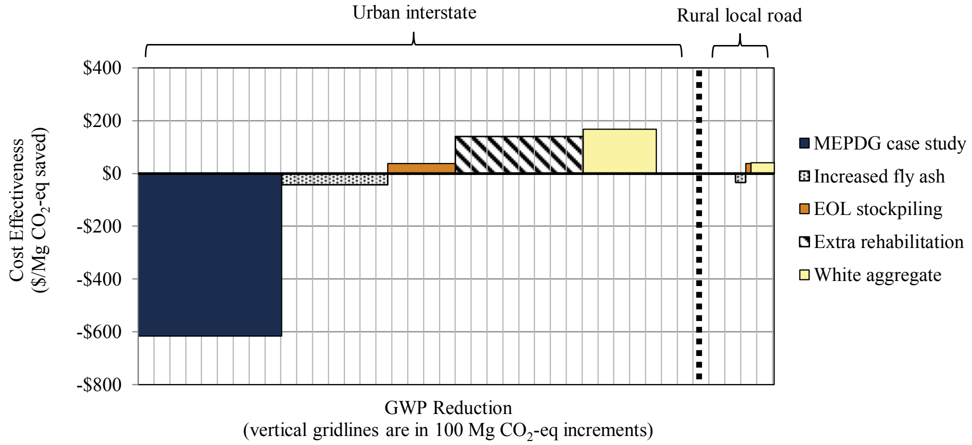

Figure 3 Cost of GWP abatement comparison of urban interstates versus rural local roads. The width of the bars represents the total reduced GWP, with the vertical gridlines representing 100 Mg CO_2-eq increments. GWP = global warming potential; Mg CO_2-eq/cl-km = megagrams carbon dioxide-equivalent.

white aggregate strategy is not practical for urban interstates: The high cost and relatively small reduction potential is a poor combination. Conversely, for rural local roads, the white aggregate strategy offers a significant GWP reduction at costs that are comparable to the price of carbon.

Discussion

The fly ash scenario is a good example of reducing embodied emissions by adjusting the amount of cement in the mix. Cement has been shown to be the largest GWP contributor over the concrete life cycle (Santero et al. 2011), so it is reasonable to assume that decreasing the cement content through the use of SCMs or optimized mix designs is a reasonable reduction approach. The results coincide with this assertion, showing a 10% to 20% reduction across all roadway classifications. The replacement of cement with a by-product of the coal combustion process also reduces costs: A metric ton of CO_2-eq corresponds to a $40 savings in material costs. Blast furnace ground-granulated slag and silica fume are examples of other SCMs that may provide similar results. It should be noted that the quality and regional availability of the fly ash (and other SCMs) will affect the efficacy of this reduction option; this study assumes high-quality class F fly ash that is practically available. Moreover, any health hazard concerns associated with fly ash are considered outside the scope of this study.

The driving forces behind the cost-effectiveness of using white aggregates to increase albedo are the depth of the concrete and the local availability of the aggregates. If an extra haul distance of 50 km is necessary to acquire white aggregates, this is a relatively cost-effective GHG reduction strategy for low-volume classifications (e.g., \$41/Mg CO_2-eq reduced for rural local roads). As the extra haul distance increases, both the cost and total emissions increase, causing the cost-effectiveness to quickly rise to levels well above the price of carbon. Considering that white aggregates may not be locally available for many projects, this strategy is not universally applicable. This strategy favors low-volume classifications because of the thinner concrete layer needed for the structure. Because albedo is a surface property, pavements with high surface-area/concrete-thickness ratios will have better cost-effectiveness: Only the fine and coarse white aggregates at the top of the structure will contribute to the albedo reduction. Alternatively, concrete overlays and two-lift concrete structures could take advantage of this concept by utilizing the albedo benefits of white aggregate while minimizing the "wasted" white aggregates in the structure.

Facilitating the natural carbonation process of recycled concrete aggregates presents an opportunity to sequester a considerable amount of the CO_2 released during cement manufacturing. Stockpiling and exposing recycled aggregate for 1 year is a relatively cost-effective approach (\$31/Mg CO_2-eq reduced), but standard practices of DOTs and other stakeholders may make this an impractical method. In particular, recycled concrete aggregates tend to be used quickly after they are processed, sometimes even immediately in the case where a mobile crushing unit is available at the construction site. Moreover, if this strategy were continuously applied for many pavements, the result would be an effective removal of some tonnage of aggregate supply from the available stock. The effect would be an induced demand for virgin aggregate to replace the lost stock—something that a more thorough LCA might consider within its boundaries. Although EOL carbonation arguably is most effective when the recycled concrete aggregate is directly exposed to the environment, research shows that even buried crushed concrete sequesters a significant amount of CO_2 (Collins 2010). If EOL stockpiling is considered impractical, then engineers should at least consider alternative methods of promoting carbonation at the end of the concrete pavement life cycle.

Adding an extra rehabilitation is potentially a cost-effective method for reducing emissions of high-volume roadways, although the results presented here seem to suggest otherwise. The representative structures and inputs are for average conditions across the 12 roadway classifications and thus do not capture many outlying scenarios—such as those with high traffic volumes and/or high IRI values—that could benefit from this strategy. Adding an extra rehabilitation for urban interstates has a cost-effectiveness of \$140/Mg CO_2-eq reduced (significantly higher than the price of carbon), but are only modeled for the average traffic of 79,000 vehicles per day. With volumes ranging up to 130,000 and higher on some urban interstates, an extra rehabilitation could provide significantly better cost-effectiveness for pavements under different conditions. Moreover, the roadways modeled here are in relatively good condition at year 10, which is when the extra rehabilitation is assumed to occur: The IRI at year 10 is 1.2 m/km, with grinding assumed to reduce the roughness to 1.0 m/km. Roadways with higher pre-rehabilitation IRI values will benefit more from grinding, leading to larger emission reductions and better cost-effectiveness. Considering that the average urban interstate has an IRI of 1.5 m/km (FHWA 2008), there should be ample opportunities to reduce emissions through diamond grinding.

Avoiding overdesign shows significant potential as a cost-effective method of reducing GHG emissions. Using MEPDG (rather than AASHTO 1993) to design the pavements essentially reduces the thicknesses of the concrete and/or base layers, thus mitigating the costs and emissions from the associated materials and processes. MEPDG is climate specific, so data from a particular location (Oxnard, CA, USA) were used. A moderate climate was specifically chosen to show the potential GWP and cost benefits of MEPDG-derived designs, but it should be noted that the results may differ in other climates. The perceived advantage of using MEPDG (or other advanced design procedures) to avoid overdesign will differ from project to project. In some cases, the baseline design may already be relatively accurate (or even underdesigned), thus leaving little to no opportunities to reduce emissions using this technique. Additionally, any benefits associated with avoiding overdesign are correlated to the analysis period itself: Overdesigned pavements will outlast their intended service life, thus providing service beyond the analysis period. This study operates under the assumption that pavements are strategically designed for a particular service life and thus an efficient design is one that meets that service life and minimizes the risk of functional obsolescence (Santero et al. 2010).

Conclusions

There are multiple approaches to reduce GHG emissions of concrete pavements. Reducing embodied emissions (the quantity and emission intensity of the materials and designs) can be complemented by increasing the pavement albedo, increasing carbonation at the EOL, and decreasing the fuel consumption of vehicles during the use phase. Each of these approaches are explored using representative strategies: reducing embodied emissions by increasing fly ash content and avoiding overdesign; increasing albedo by using white aggregate; increasing carbonation through EOL stockpiling; and reducing vehicle fuel consumption by adding an extra rehabilitation.

The analyzed designs and input parameters are meant to represent average concrete structures and conditions for each of the FHWA roadway classifications. In reality, there is a significant variation within each roadway classification, making it difficult to adopt a single representative structure. Concrete pavement designs will vary significantly from one pavement to the next, changing based on regional climate, local design practices, budget, service life, material availability, and other factors. For instance, urban interstates routinely support between 30,000 and 130,000 vehicles per day (FHWA 2008), but the weighted average (79,000) is used in this analysis. This not only affects operating emissions (e.g., roughness-related vehicle fuel consumption), but also the materials and geometry of the structure. This approach is useful in generally characterizing a large breadth of pavement functions, but may also fail to adequately capture the impacts caused by atypical structures within each classification. Project-specific analyses are better suited to accurately quantify the impacts associated with a particular, well-defined pavement. Even with the generalized approach adopted in this research, several overarching conclusions can be drawn:

- Significant GHG emission reductions are possible. Over half of the scenarios result in emissions reductions greater than 150 Mg CO_2-eq per cl-km, with high-volume roadways generally offering higher absolute reduction potentials as a result of their more massive designs and higher traffic volume. Relative to the unimproved baseline designs, over half of the scenarios reduce emissions by over 10%. Relative emission reductions tend to be greater for low-volume roadways because of the combination of small baseline emissions, disproportionality of albedo with structure depth, and larger dependence on materials-based emissions.
- There are cost-effective methods to reduce GHG emissions for concrete pavements. Both embodied emissions strategies produce negative cost-effectiveness values, meaning that costs and emissions are saved simultaneously. The strategies for increasing albedo, increasing carbonation, and reducing vehicle fuel consumption have positive cost-effectiveness values, but there are scenarios where each is comparable to the price of carbon. Evaluating economic impacts alongside emission reduction potentials is essential in order to identify the feasibility of implementing a given reduction strategy.
- The emission reduction potential and cost-effectiveness of a GHG emission reduction strategy changes based on the classification of the roadway. Scarcity concerns aside, increasing albedo by using white aggregate stands out as an effective method of reducing GWP for low-volume roadways. For high-volume roadways, the inefficient use of the specialty material (only a small fraction of the aggregates contribute to the increased albedo) limits the reduction potential and disproportionately increases the costs, resulting in a poor effectiveness for these roadways. Conversely, adding an extra rehabilitation in order to reduce vehicle fuel consumption has the potential to be effective on high-volume roadways, but is not effective (and potentially counterproductive) for low-volume roadways.

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Notes

1. One vehicle-kilometer (km, SI) ≈ 0.621 vehicle-miles (mi).
2. One kilogram (kg, SI) ≈ 2.204 pounds (lb). One cubic meter (m^3, SI) ≈ 35.3 cubic feet (ft^3).
3. Throughout this article, $ indicates U.S. dollars.

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Supporting Information

Additional Supporting Information may be found in the online version of this article at the publisher's web site:

Supporting Information S1: This supporting information provides several tables with input data for baseline scenarios, the roughness index (IRI) and design thickness for various strategies, and estimates of global warming reduction potentials and cost effectiveness for different scenarios.