Mitigating Climate Change with Reflective Pavements

CSHub Topic Summary | November 2020

MIT CONCRETE SUSTAINABILITY HUB

Pavements and the Climate

The U.S. boasts the world's most extensive road network—4 million miles in total. And those roads exert a direct impact on the climate.

That's because pavements, like any other surface, can alter the climate depending on the proportion of light they reflect. That proportion of reflected light is known as albedo. Darker surfaces, which have a lower albedo, absorb more radiation and generally warm the climate, while lighter surfaces, which have a higher albedo, do the opposite.

For cities, which are densely composed of lower albedo surfaces, this means more intense heatwaves and higher air temperatures—a phenomenon called the urban heat island

Key Takeaways:

- The reflectivity of all surfaces affects the climate. The measurement of surface reflectivity is known as albedo.
- Reflective pavements could lower air temperatures by over 2.5 °F and reduce the frequency of heatwaves by 41% across all U.S urban areas.
- Reflective pavements could offset enough CO_2 to remove the equivalent of around 4 million cars from the road each year.
- It's vital to implement reflective pavements according to their contexts to avoid burdens that can outweigh their benefits.
- Despite potential increases in building energy demand, reflective pavements can offer significant net benefits.

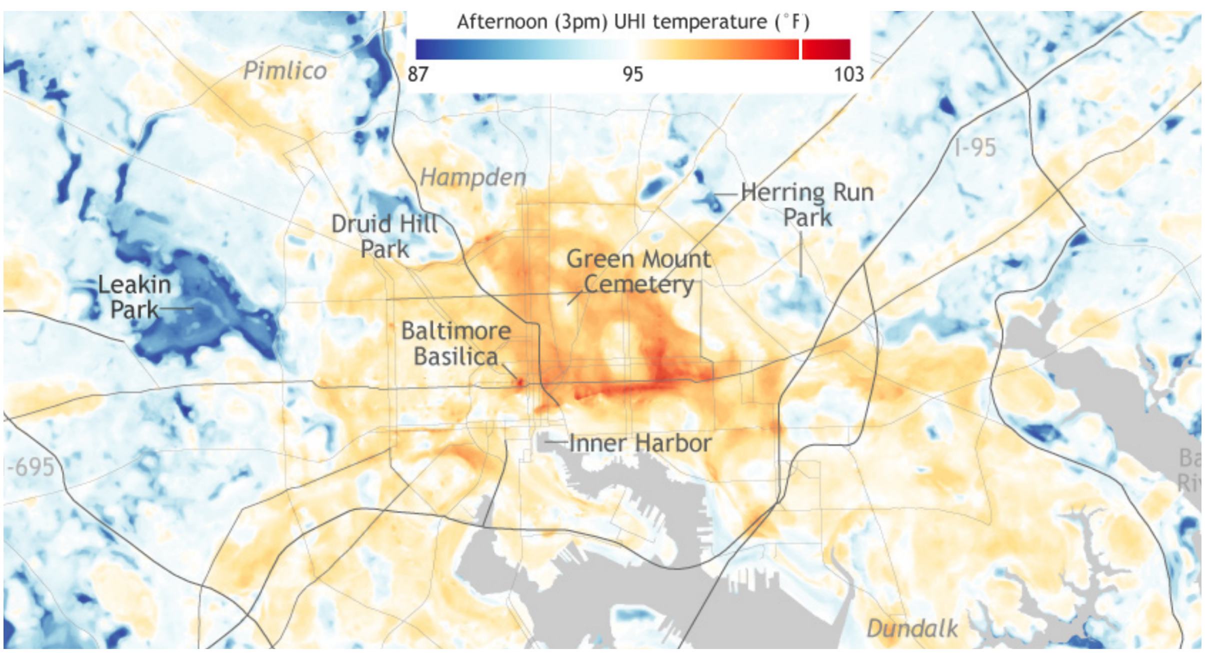

Figure 1. A map displaying air temperature variations in Greater Baltimore, Maryland due to the urban heat island effect. Credit: NOAA

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effect (UHI) (**See Figure 1**). As a result, many cities have begun to increase the reflectivity of one of their most abundant surfaces: pavements.

Since they compose around 40% of urban space, pavements have considerable potential to mitigate climate change and urban heat islands. Research at the MIT Concrete Sustainability Hub finds that maximizing that potential demands close consideration of context.

What are Reflective Pavements?

As their name suggests, reflective pavements possess properties that make them more reflective than conventional pavements.

While a conventional pavement might have an albedo of 0.1 (meaning that it reflects 10% of the radiation it receives), reflective pavements have albedos of 0.3 or higher on average—meaning they are at least 3 times as reflective.

There are several ways to make pavements reflective. The first is through material choices. Concrete pavements, for example, naturally possess a higher albedo (around 0.3) than other conventional options and for that reason are considered reflective. Their natural reflectivity can be further increased through the use of brighter additives such as slag, portland limestone cement, or reflective aggregates (**Figure 2a&c**). Another option is to apply reflective coatings on top of pavements (**Figure 2b**). Pavements with reflective coatings typically possess the greatest reflectivity and can have albedos of 0.4 or higher.

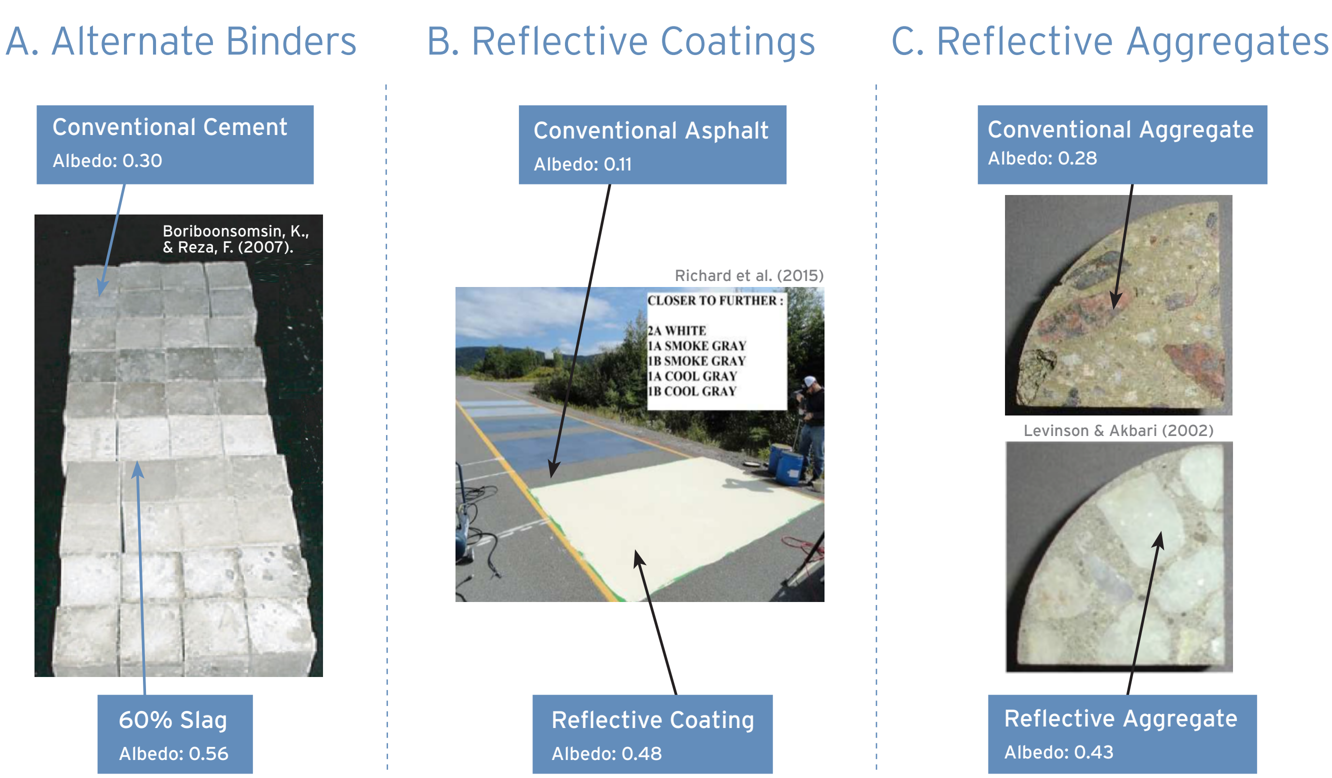

Figure 2. A comparison between conventional and reflective paving strategies. Changes to the binders, aggregates, or surface properties of a pavement can substantially increase its albedo.

Regardless of which option is chosen, reflective pavements are most affordable when implemented during the construction or rehabilitation process. This is because the expense of reflective strategies is insignificant compared to the construction of the pavement itself. Reflective pavements can also exhibit some cost savings: if sourced locally, reflective paving materials, such as light-colored aggregates or binders, may cost less than conventional paving materials.

Mitigation of Extreme Heat

The most apparent climatic impact of reflective pavements is on local air temperatures. While conventional low albedo pavements absorb more solar radiation and release that radiation as heat, higher albedo pavements reflect a greater proportion of radiation and therefore emit less heat. As a result, they lead to comparatively lower local air temperatures. Using a 20-year climate simulation, CSHub found that a moderate increase in pavement reflectivity could decrease urban air temperatures by 2.5 °F across the U.S. In Houston, the nation's 4th largest city, heatwaves would fall by as much as 59%. Across all U.S. urban areas, the number of heatwaves would fall by around 41% (**See Table 1**).

A Climate Change Solution

Reflective pavements also impact the global climate. Radiation reflected into the top of the atmosphere alters the Earth's radiative balance. This process, known as a radiative forcing, can offset some of the radiation trapped by greenhouse gases, which can directly mitigate climate change.

Table 1. Changes in the number of number of heat waves, number of days when the heat index exceeds 41ºC (HI41) (danger heat advisory), and the changes in summer daily maximum temperature estimated as the 20-year mean differences for a 0.2 increase in pavement albedo in urban areas.

	Change in Heatwaves	Change in HI41 Days	Change in Summer Max Air Temperature
All U.S. urban areas	-41%	-50%	-2.5 ºF
Los Angeles	-42%	-95%	-2.7 ºF
Chicago	-27%	-38%	-2.3 ºF
New York City	-49%	-55%	-2.5 ºF
Houston	-59%	-55%	-2.7 ºF

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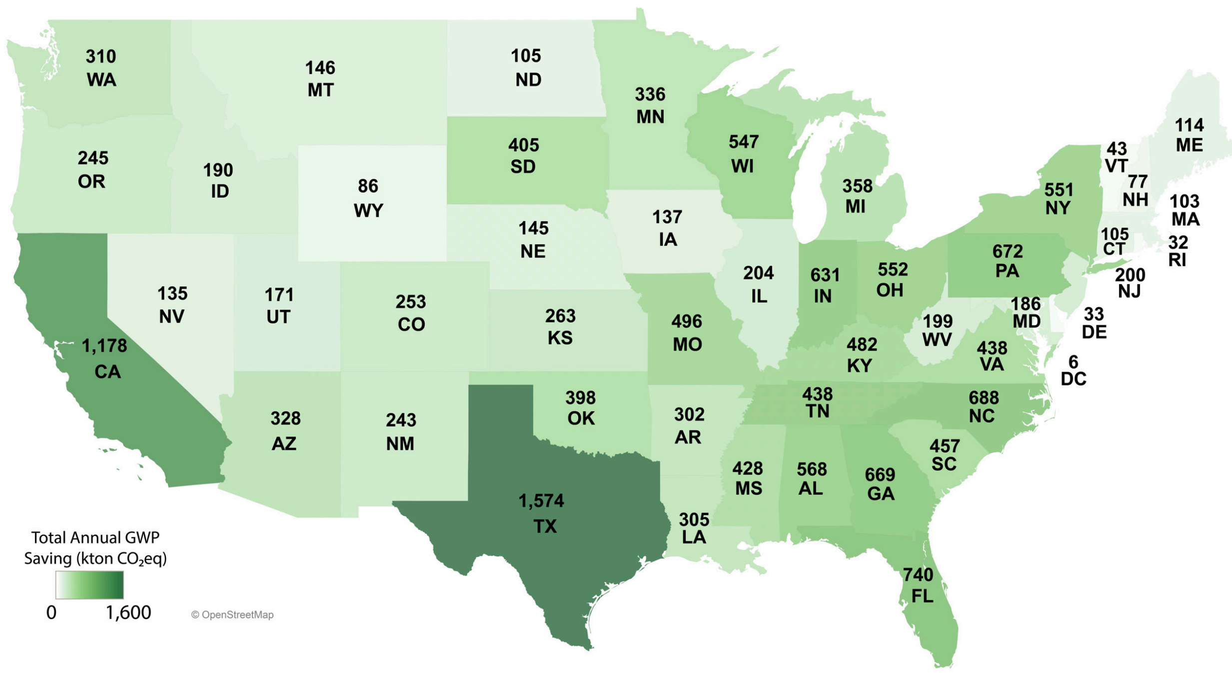


Figure 3. The annual global warming potential savings due to increasing the surface reflectivity of all pavements across the continental U.S.

An increase in pavement albedo on all U.S. roads, a CSHub model estimated, would offer climate benefits of more than 17.45 Mton CO_2-eq per year due to radiative forcing—equivalent to the amount of CO_2 produced by around 4 million cars driven for one year. These benefits, however, varied state-to-state due to differences in the size of their pavement networks and their location and climate (**See Figure 3**). Rural areas, in particular, saw the greatest radiative forcing benefits since their pavements had few obstructions and therefore received and reflected more radiation.

Contextual Variations

While reflective pavements will always lower air temperatures and exert radiative forcing benefits, they can also influence the energy consumption of adjacent buildings. This is in part due to the complexity of the built environment.

As they lower air temperatures, reflective pavements can alleviate the need for air conditioning in the summer and reduce emissions. In the winter, though, that same temperature reduction can exacerbate heating burdens and related emissions.

Furthermore, not all of the light reflected by a pavement reaches the top of the atmosphere. Instead, some reflected light—called incident radiation—often strikes nearby buildings and warms them. The incident radiation from reflective pavements can therefore counteract the effects of lower air temperatures, increasing cooling demand and greenhouse gas emissions in the summer while reducing them in the winter (**See Figure 4**).

These impacts on building energy demand are most pronounced in cities due to what's known as urban morphology (**See Figure 5**). Urban morpholo-

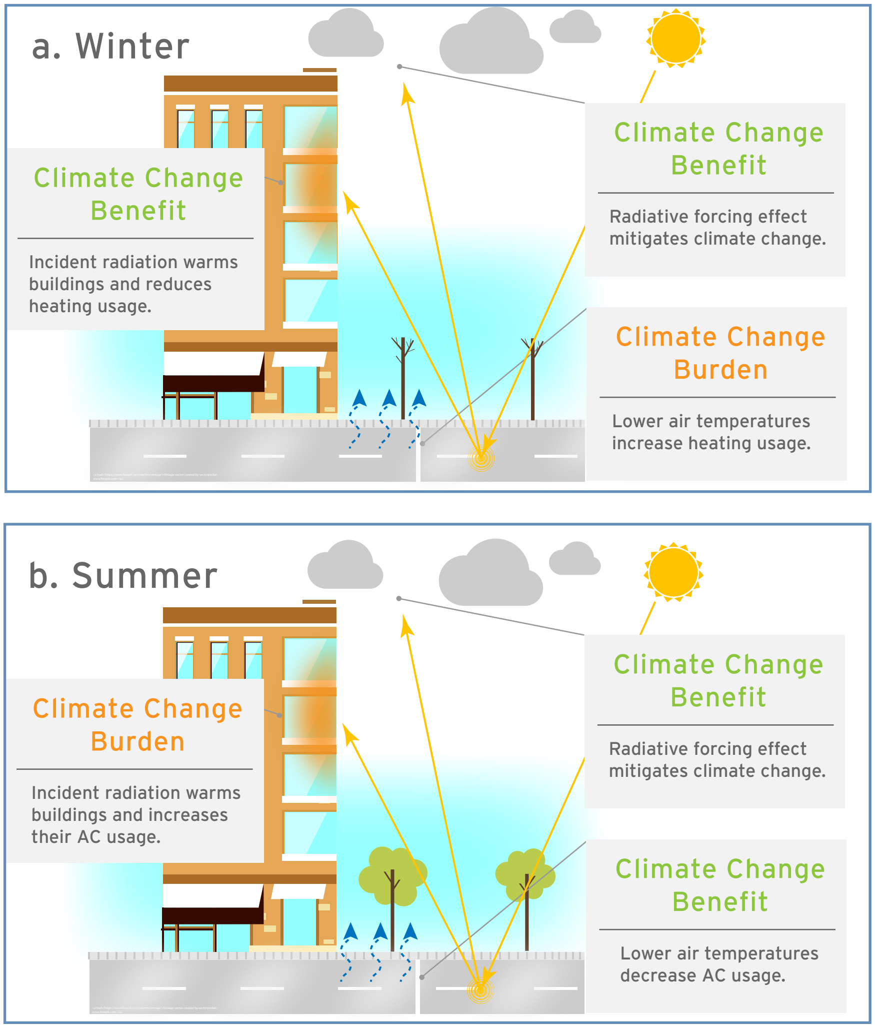
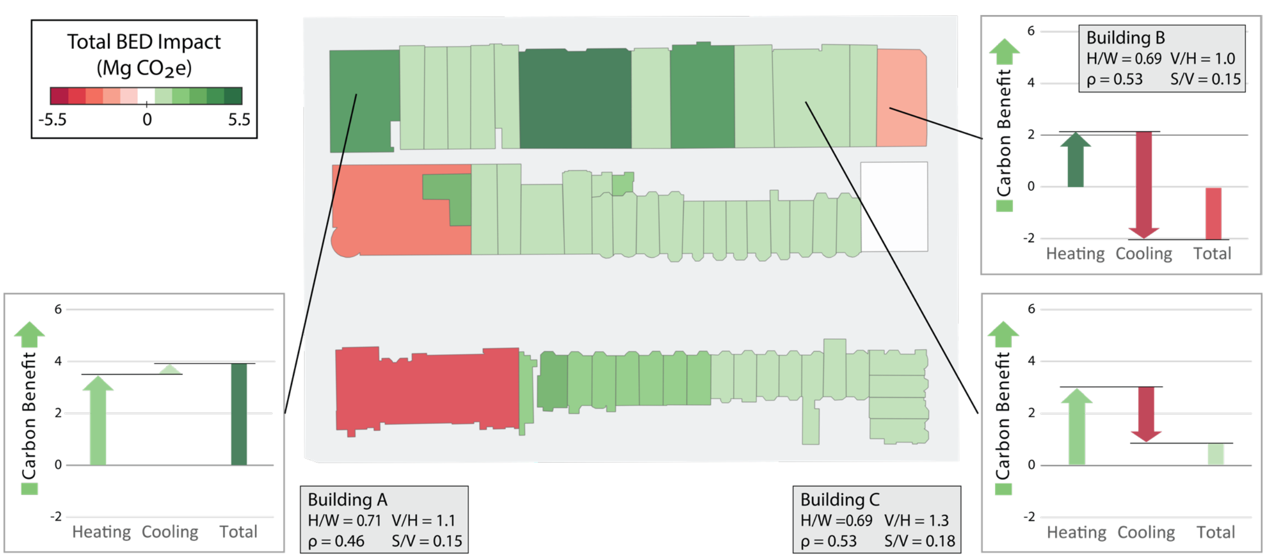


Figure 4. The climate change impacts of reflective pavements in cities during winter (**a**) and summer (**b**). While reflective pavements always reduce air temperatures and exert radiative forcing benefits, their impacts on building energy demand oscillate seasonally due to changes in HVAC demands and air temperatures.

Figure 5 (below). The effects of increasing pavement albedo by 0.2 on building energy demand (BED) depend upon urban morphology. These effects can vary significantly even within a single block, as seen in the figure below that shows an actual set of buildings in Boston. BED is the greenhouse gas emissions associated with cooling and heating. The symbols and numbers for each building define its shape and the density of surrounding buildings.



gy refers to the form of a city, which can include the heights and footprints of structures and the layouts of streets.

The distinctive urban morphology of city centers—typically composed of dense and tall structures along narrow streets—means that a greater proportion of incident radiation will strike buildings and change their energy demand. And since city centers consume a substantial amount of energy to begin with, any change in their building energy demand due to reflective pavements will have a greater climate change impact than in less developed or rural areas.

Ultimately, the implementation of reflective pavements involves several tradeoffs. A city must balance a pavement's effect on both air temperatures and surrounding structures to best mitigate climate change impacts. To understand how to strike that balance, CSHub investigated the impact of increasing pavement albedo in two large American cities: Boston and Phoenix.

Case Study: Boston and Phoenix

Besides their status as state capitals, Boston and Phoenix have seemingly little in common. While Boston is an old city of considerable density with a continental climate, Phoenix has a sprawling, mostly low-rise form and experiences some of the highest air temperatures among U.S. cities.

CSHub found that these different characteristics dictated the consequences of implementing reflective pavements in each city.

While both Boston and Phoenix saw decreases in summer air temperatures due to an 0.2 increase in pavement reflectivity, those decreases were of different magnitudes. Boston experienced a 1 to 2.7 °F decrease in summer air temperatures while Phoenix would see a decrease of 2.5 to 3.6 °F. This was a consequence of Phoenix's climate: since the city experiences more sunny days annually and receives more intense solar radiation, reflective pavements would exert a greater influence on air temperatures. These same climatic characteristics meant that Phoenix would also experience a 26% greater climate change mitigation benefit from radiative forcing than Boston.

The climate change impacts of reflective pavements also varied *within* each city. In Boston's dense core, where tall buildings obscured light from reaching narrow streets, reflective pavements led to a small reduction in annual building energy demand. However, on account of several miles of open freeways in that downtown core, reflective pavements exerted a substantial radiative forcing effect that enabled even greater GHG emission savings. Overall, reflective pavements in Downtown Boston led to net GHG savings (**See Figure 6**).

Reflective pavements in Downtown Phoenix, though, led to a net GHG burden. Climate, latitude, and the spacing of buildings all caused incident radiation from reflective pavements to increase cooling demand in the summer. Neither radiative forcing nor reduced heating demand in the winter came close to offsetting the emissions from cooling-induced energy demand (**See Figure 7**).

In suburban areas of both cities, reflective pavements led to net benefits. Most of these benefits, due to low local energy demands and sparse surroundings, came from radiative forcing.

As demonstrated in this case study, the climate change impacts of reflective pavements are highly

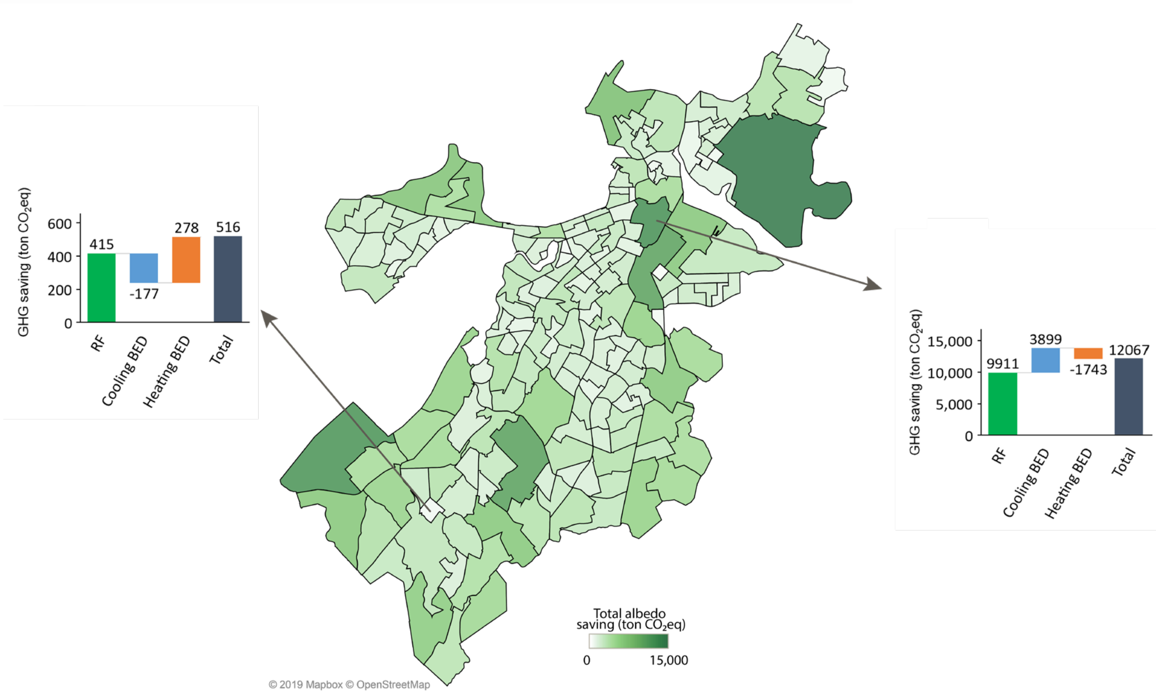


Figure 6. GHG savings from building energy demand (BED) and radiative forcing (RF) over 50 years in Boston, MA due to a 0.2 increase in pavement albedo by using portland cement concrete instead of asphalt. 'Cooling BED' refers to cooling usage, while 'Heating BED' refers to heating usage. Negative values indicate a GHG burden.

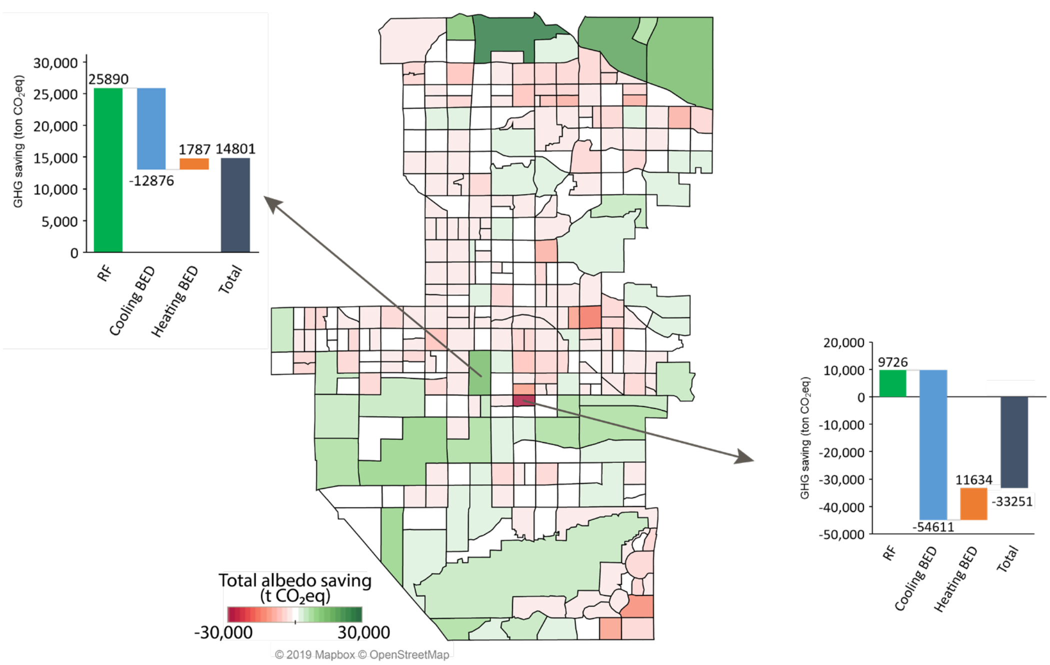


Figure 7. GHG savings from building energy demand (BED) and radiative forcing (RF) over 50 years in Phoenix, AZ due to a 0.2 increase in pavement albedo by using portland cement concrete instead of asphalt. 'Cooling BED' refers to cooling usage, while 'Heating BED' refers to heating usage. Negative values indicate a GHG burden.

context-specific. Though they will always lower air temperatures, their net emissions will vary greatly depending on a city's unique climate and urban morphology.

Beyond Albedo

While albedo can compose a significant fraction of a pavement's total emissions, the selection of pavement designs should also consider all phases of the life cycle: materials production, construction, end-of-life, and use.

The use phase, which tends to compose the majority of a pavement's emissions, is made up of a variety of impacts. In addition to albedo, they include excess fuel consumption from road quality, carbonation (a natural process of CO_2 uptake in concrete), and lighting. Just as with albedo, the impacts of each of a pavement's life cycle phases will vary by context. Researchers tallied up these lifetime impacts—including albedo—in Boston and Phoenix to determine where certain pavement designs would emit the least.

In neighborhoods of Boston and Phoenix with substantial traffic, excess fuel consumption from road quality was the predominant contributor to life cycle emissions (**See Figures 8 & 9**). Concrete pavements, due to their rigidity and durability, generated the fewest life cycle emissions in these areas.

In downtown Phoenix, however, which experiences relatively low vehicle throughput, reflectivity is the primary contributor to a pavement's lifecycle emissions (**See Figure 8**). Asphalt pavements, on account of their low reflectivity, would therefore generate the fewest life cycle emissions in this area as they wouldn't increase building energy demand.

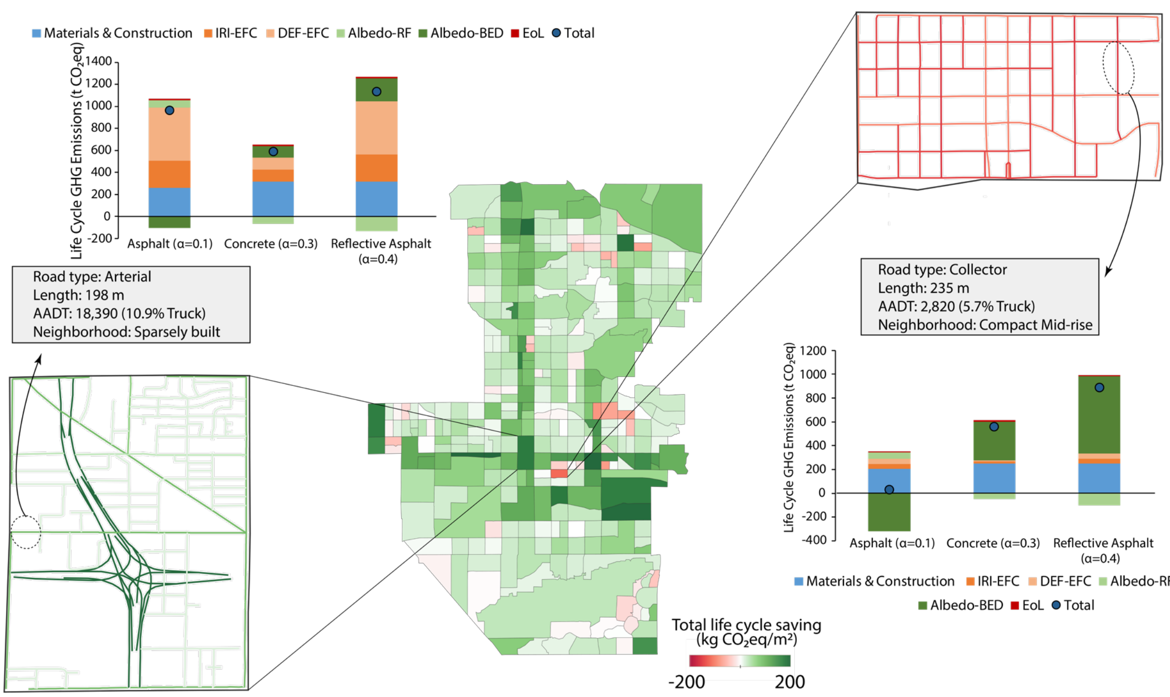


Figure 8. Life cycle GHG savings of replacing asphalt concrete with portland cement concrete in Phoenix, AZ. The bar charts compare life cycle GHG emissions of two cool pavement strategies to the currently built asphalt for the specified road segment.

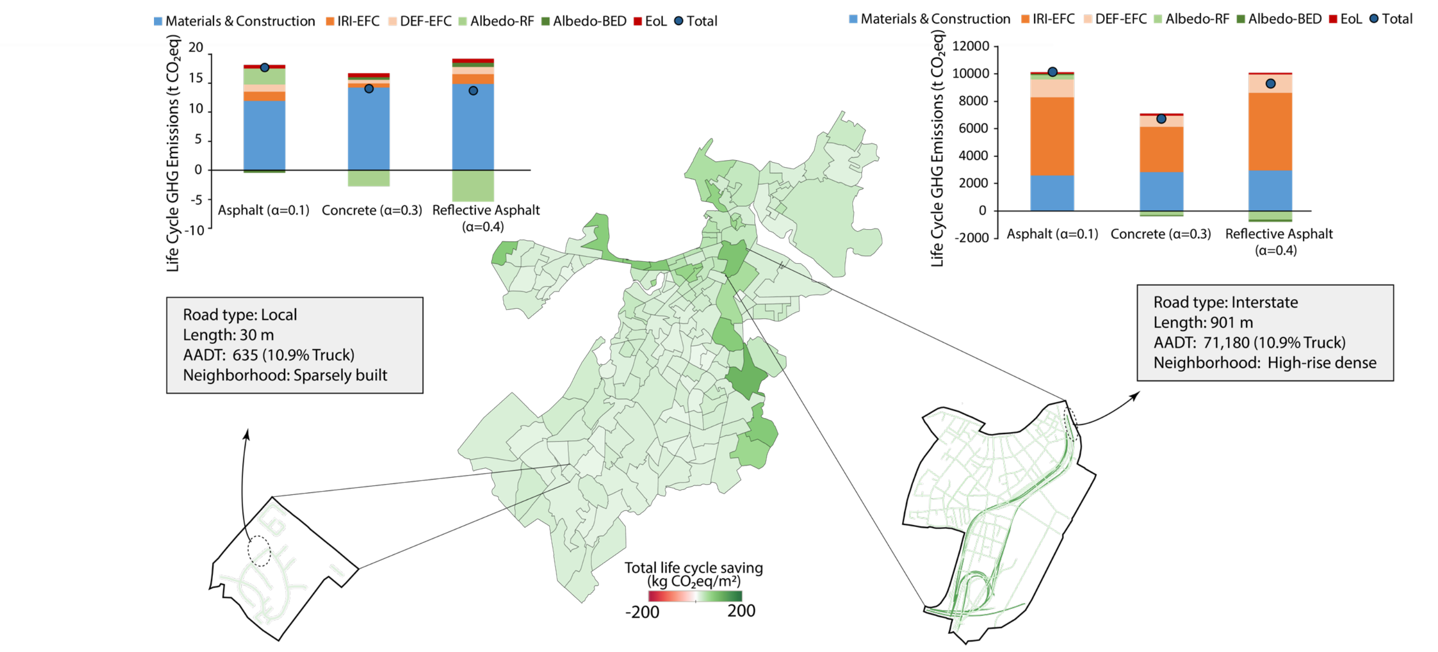


Figure 9. Life cycle GHG savings of replacing asphalt concrete with portland cement concrete in Boston, MA. The bar charts compare life cycle GHG emissions of two cool pavement strategies to the currently built asphalt for the specified road segment.

Reflective asphalt pavements proved most beneficial in Boston's more sparsely built neighborhoods. Little shading and small building frontages led to relatively large radiative forcing benefits that offset the increased fuel consumption caused by asphalt pavement properties (**See Figure 9**). This offset occurred because of the low levels of traffic experienced in these areas (roughly 1% of Downtown's levels).

Overall, both cities saw significant GHG savings when the lowest emitting pavement types were implemented. Over a 50-year period, Boston would experience around 1.5 million metric tons of GHG savings. Phoenix would see an even greater impact: 6 million metric tons of GHG savings over the same period.

Reflective pavements, then, can generate substantial GHG emissions savings—but only when implemented based on their specific contexts. Though their context-dependent nature can make their effects hard to generalize, some trends have emerged. In dense, urban neighborhoods, the reflectivity of pavements matters most for pavement life cycle emissions, while in heavily trafficked areas it has a smaller influence.

Future Considerations

There's more to a neighborhood than the expanse of its pavements and the average height and density of its structures. Future CSHub research will investigate how neighborhood heterogeneity can influence the energy consumption of specific structures. Attributes such as the angles, details, and colors of façades, as well as the presence of both stationary and moving vehicles, will all be incorporated into the model. The goal is to be able to rapidly identify how reflective pavements would alter the specific climate change impact of any given structure, neighborhood, or city anywhere in the world.

Related Links:

- CSHub Albedo Research
- CSHub Pavements Research
- CSHub Urban Physics Research

Citation:

AzariJafari, H., Kirchain, R., Gregory, J. "Mitigating Climate Change with Reflective Pavements." CSHub Topic Summary. 2020. Volume 2020, Issue 3.

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Images used in Figure 2 (from left to right):

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