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Policy Analysis

Urban-Scale Evaluation of Cool Pavement Impacts on the Urban Heat Island Effect and Climate Change

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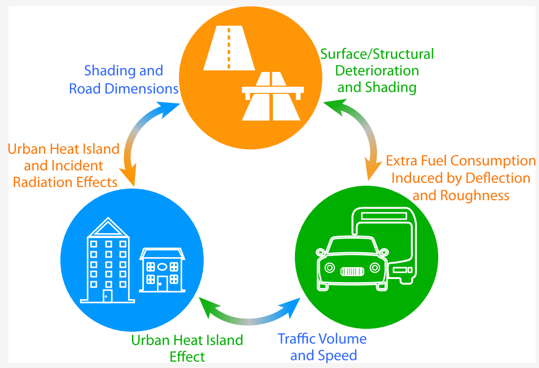
ABSTRACT: We implemented a context-sensitive and prospective framework to assess the global warming potential (GWP) impacts of cool pavement strategies on specific roads for different cities. The approach incorporates several interconnections among different elements of the built environment, such as buildings and urban road segments, as well as the transportation fleet, using specific building and pavement information from an urban area. We show that increasing pavement albedo lowers urban air temperatures but can adversely affect the building energy demand in the areas with high incident radiation exposure. The heating energy savings and the radiative forcing effect improve the GWP savings in cold and humid climate conditions. The total GWP savings intensity is sensitive to the city morphology and road traffic. The probabilistic results show that cool pavement strategies can offset 1.0−3.0% and 0.7−6.0% of the total GHG emissions of the U.S. cities Boston and Phoenix, respectively, for a 50-year analysis period. The worldwide range of savings can be as large as 5.0−44.7 Gt of CO_2 eq. A paradigm shift in pavement strategy selection is required in most neighborhoods.



KEYWORDS: *built environment, urban heat island effect, vehicle fuel consumption, city morphology, radiative forcing*

1. INTRODUCTION

By midcentury, two out of every three persons on the planet will be living in urban areas.[1] These growing urban populations face two simultaneous climate challenges: extreme heat events attributed to urban heat island (UHI) effects and global climate change (GCC). Cities want to take actions that address UHI without compromising progress toward global climate goals.

Variations in the magnitude of the UHI effect have been attributed to differences in urban characteristics including (a) the capacity for evapotranspiration (EVAP),[2] (b) the efficiency of convective heat transfer (CONV),[3] (c) net radiation into the urban area (NETRAD),[3,4] (d) the magnitude of sensible and latent anthropogenic heat flux (FLUX),[5] and (e) the heat storage capacity of the built environment (HEATCAP).[6] To mitigate UHI, a number of strategies have been proposed that modify these urban characteristics, including (1) removing anthropogenic heat sources (which impacts FLUX),[7] (2) alteration of urban configuration (CONV, NETRAD),[8] (3) increased urban vegetation (EVAP, NETRAD, HEATCAP),[9] as well as installation of so-called (4) cool roofs (EVAP, NETRAD, HEATCAP)[10] and (5) cool pavements (EVAP, NETRAD, HEATCAP).[11] Although there are some cases of mitigating the UHI effect using the EVAP and HEATCAP mechanisms (e.g., pervious pavements for parking lots), a more common approach is the use of cool roofs and cool pavements, which have surfaces with higher solar reflectance (albedo) and lower thermal emittance than a conventional roof or road.[12] Analyses of most of these strategies, including reducing heat flux, green and reflective roofs,[10,13−15] and increased urban vegetation,[16] have consistently reached conclusions that they were both effective at mitigating UHI and would generate corresponding reductions in greenhouse gas (GHG) emissions. Analyses of cool pavements, however, have reached inconsistent conclusions. We will argue in this paper that these inconsistencies arise from differences in modeling scope and a failure to fully characterize the influence of urban context on the result. Using a high-resolution model, we will show that while there are some instances where cool pavements can generate net increases in GHG emissions, there are many more contexts where the opposite is true. It should be noted that high albedo pavements might influence human thermal comfort and driver safety. The effect, however, will be context-dependent as the local climate and neighborhood characteristics will affect the degree to which the change in air temperatures is offset by increased radiation incident on adjacent buildings (hereafter, incident radiation). In this

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document, these effects were investigated in terms of climate change impact as measured in terms of equivalent GHG emissions. However, some of the case studies of pavement reflective evaluation on human thermal comfort and vision are provided in the SI document, section S1.1.

Modeling the climate change implications of cool pavements is challenging for at least two reasons—interconnectedness within the urban context and heterogeneity of the neighborhoods. In cities, every component of the built environment is interconnected—a change in one component of the built environment not only affects its own lifecycle but also alters the environmental performance of other components. This is particularly true for pavements where their surface and thermal properties can alter the radiative balance (direct radiative forcing, RF) and the energy use of nearby buildings (by changing local ambient temperature and irradiance); their structural properties alter the fuel use of passing vehicles (by changing the rolling resistance and wasted motion energy); and their supply chains produce emissions. A comprehensive framework is required to incorporate all of these interconnections when assessing the GCC impact of different cool pavement solutions. Moreover, the urban environment is highly heterogeneous, in terms of both building configuration (morphology) and traffic patterns, making it unlikely that any single cool pavement solution will be optimal for the whole city.

Pavement albedo change alters the earth's energy balance at the top of the atmosphere, directly contributing to the GCC cause-and-effect chain, which is known as the RF effect.[17] Studies focused on the RF effect of pavements are limited but show its possible impact. Applying global average radiative characteristics, Akbari et al.[18] estimated that a pavement albedo increase of 0.15 in 26 m^2 of pavement could create an RF equivalent to removing 1 ton of CO_2 from the atmosphere (-2.55 kg CO_2 equivalent/m^2/0.01 albedo increase). Updating these values using a global climate simulation model, Menon et al.[17] reported a pavement RF effect of -3.26 kg CO_2e/m^2/0.01 albedo increase. In a recent study, the authors developed a parametric model of pavement RF that accounts for location-specific insolation and the muting effects of local shading and aerosols. The results of this model suggest an RF effect of -1.1 to -1.6 kg CO_2e/m^2/0.01 albedo increase. Given the spatial variation within a city and consequent shading from adjacent buildings, the amount of incoming and outgoing solar radiation might be different, and as a consequence, the RF effect of different roads within a city may vary.[19] Moreover, these results highlight an important positive consequence but only provide a partial picture surrounding pavement albedo modification.

Although the GHG implications of pavements have not been mapped out in a way that accounts for variation in an urban context, a body of research exists on the urban energy balance and temperature reduction effect of pavement albedo increase. As reviewed in the works of Santamouris[20] and Qin,[21] more than 10 studies have been reported in the literature that estimate the impact of pavement albedo modification on ambient temperature and, in some cases, excess building energy demand (EBED—the change in energy used by nearby buildings). All such studies report a decrease in average ambient temperature in response to an increase in surface albedo,[20,21] but the corresponding change in modeled EBED can vary from a savings to an increase. For example, Pomerantz et al.[22] estimated that the cooling EBED savings for a city-wide albedo increase of 0.2 is up to 2 kWh/m^2 per year for the state of California. The analysis by Pomerantz et al. did not include the effect of solar radiation reflected from the pavement (herein, incident radiation) on EBED. By contrast, in a study of the city of Phoenix (with similar climate conditions to California case studies), Yaghoobian and Kleissl[23] investigated the sensitivity of the EBED to canyon aspect ratio and building characteristics and found that a 0.4 albedo increase in the pavement caused a 5.3−10.9% increase in the peak cooling demand. Clearly, as the modeling elements and the captured UHI characteristics can act as competing mechanisms, there is an unanswered question as to whether pavement albedo modification provides GCC benefits (or impacts) in different locations with a variety of climate conditions.

Over the past decade, a growing body of literature has attempted to provide a more complete picture of the total life cycle impacts of changes to pavement materials. The scope of these papers varied significantly with some studies including RF and/or EBED effects of albedo change and some including different causes of excess vehicle fuel consumption due to imperfect pavement vehicle interaction (PVI). Specifically, they included PVI effects from either pavement roughness and/or pavement deflection. Table S1 in the SI summarizes these differences in scope among the LCA literature. For our discussion here, the most critical issue with these earlier LCA studies is that most estimated the impact of albedo modification by applying global average models.[24−27] In other words, albedo-related impacts were estimated by assigning a constant value per unit of the area regardless of the location and prevailing urban morphology. This approach precludes insight into the impact of the local context. Two papers[11,28] diverge from this group through their use of more complex simulations that allow for consideration of urban context. Using empirical models of temperature change and energy balance developed by Li,[29] Azarijafari et al.[28] analyzed the lifecycle impacts of pavement albedo modification including both EBED and RF as well as PVI effects. They found that increasing pavement albedo can induce a net annual GCC burden of 0.34 kg CO_2e/m^2 per 0.2 albedo increase in cold climate conditions (Quebec, Canada). Gilbert et al.[11] applied a single-layer urban canopy model within a broadly applied climate simulation as part of a life cycle assessment of various pavement types. They found that a 0.2 albedo increase results in a net EBED saving of 0.8−1.0 CO_2e/m^2 per year in the city of Los Angeles under different scenarios of reflective coating and concrete overlay. Context-specific PVI and RF effects were not calculated.

In the end, although the UHI benefits of cool pavements in different locations are well established,[20,21,30] the net GCC impact is not yet settled. This is true because previous studies have not had a consistent scope and did not explore the impact of the local urban context. The microclimate, morphology, and prevailing traffic vary significantly within a city.[31−33] These differences play an important role in the net impact of pavement albedo modification.

The objective of this study is to develop a framework that can capture the impact of cool pavement strategies on both the UHI effect and climate change in cities considering the interconnections of buildings, vehicles, and pavements. The framework can be used for individual pavement segment analyses within specific neighborhoods and aggregated across an entire city. Using this framework, several cool pavement strategies were evaluated for two cities with different climates:

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Boston and Phoenix. Results of this analysis show that cool pavements can induce both burden and benefit, but when applied appropriately, both lower urban air temperatures and provide net GCC benefits equal to 1−6% of the total city GHG emissions.

2. METHOD OVERVIEW

To quantify the potential life cycle GHG emissions associated with cool pavements, including the implications of changes to surface albedo, we developed a framework to model the pavement life cycle from materials extraction to end-of-life including the interaction among pavements, buildings, and vehicles.

This framework comprehensively covers the location-specific impacts of cool pavements on different parts of the built environment, including the embodied impacts associated with the pavement materials and the interaction among pavements, vehicles, and building energy consumption. These elements and their interconnection are shown in Figure 1. Some

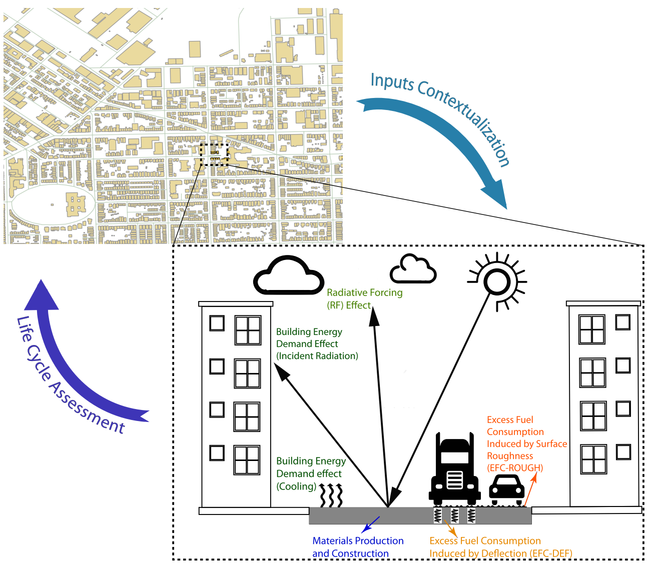

Figure 1. Overview of the methodology and life cycle components of pavements in urban areas. Considering the interconnection among the elements of the built environment, a top-down approach was developed to capture the effect of cool pavement strategies on the GHG balance of cities.

components of this framework have been described in previous publications but are summarized here for completeness. We apply the modeling framework to the roads and buildings in two cities.

2.1. Analytical Scope. The framework applied here is intended to capture the impacts of all activities that current knowledge allows to attribute to the choice of materials associated with a pavement's surface course. Formally, this includes activities associated with materials extraction and refinement (including any transformation and transportation to the pavement site), construction, maintenance and rehabilitation (M&R), pavement use, and end of life (including any disposition of materials during M&R). Framed in this way, and following norms within the pavement literature, the analysis presented herein presumes a 50-year analysis period of the existence of the road and therefore excludes consequences such as additional traffic because of its presence.

The primary novelty of this work derives from developing and applying models that provide insight into the influence of local urban context on impacts that occur during pavement use. As such, those models are described in greater detail, and modeling of all other life-cycle stages is summarized in the following section.

2.2. Modeling: Impacts from Materials, Construction, and End of Life. The embodied impacts of pavements include the emissions from the supply chain of construction materials and reflective coatings used for increasing pavement albedo as well as the construction activities required to place those materials. Hence, the bill of materials and required equipment for the reconstruction of the currently existing urban roads are included in the scope of analysis. Moreover, the quantity and type of materials and equipment used for maintenance and repair of the road segments are incorporated into the analysis based on established patterns of pavement deterioration and pavement performance thresholds (see SI spreadsheets S1, S3, and S4). The transportation required to move these materials from production plants to the construction site and from the site to a landfill or recycling plant were included in the analysis. Input parameters and pavement designs related to the embodied impacts of pavements are presented in SI spreadsheet S1.

2.3. Modeling: Impacts during Pavement Use. During pavement use, pavement material properties, including surface albedo, lead to UHI and GCC impacts both directly and through the interaction among pavements, vehicles, and buildings. The framework applied here captures three of these interactive effects. These are causing (1) excess fuel consumption in vehicles due to both pavement roughness and stiffness, (2) excess building energy demand, and (3) direct radiative forcing.

Vehicle Excess Fuel Consumption. The interaction between pavement and vehicle occurs because pavement characteristics alter the energy required for cars and trucks to move along a roadway. This effect is measured in terms of excess fuel consumption (EFC), that is, the fuel consumption induced in the fleet in excess of what it would require on an ideal pavement. EFC is attributed to differences in both pavement structural response (primarily pavement deflection)[34] and surface roughness[35] (these two effects will be labeled as EFC-DEF and EFC-ROUGH, respectively). Pavement materials can induce significantly different amounts of EFC in passenger vehicles and trucks. Different designs will deflect and deteriorate (and become rougher) at different rates. In addition, the rate of road surface deterioration varies according to traffic volume and speed. Both effects are time-dependent and location-specific. Mechanisms and modeling approaches for estimating the EFC induced by pavement characteristics are presented in the SI document, section S1.1.1. Details on the modeling of EFC including the modeling of deterioration rates for each road type are presented in the SI spreadsheet. These models were applied to estimate pavement deterioration and EFC for every pavement segment in the two case cities.

Excess Building Energy Demand (EBED). Pavement materials affect building energy demand by altering both the local ambient temperature (the UHI effect) and the magnitude of radiative energy incidents on the building. The Urban Weather Generator (UWG)[36] was used to estimate ambient temperatures and precipitation for each neighborhood. To generate these estimates, UWG considers differences in urban morphology, material properties (including surface albedo and

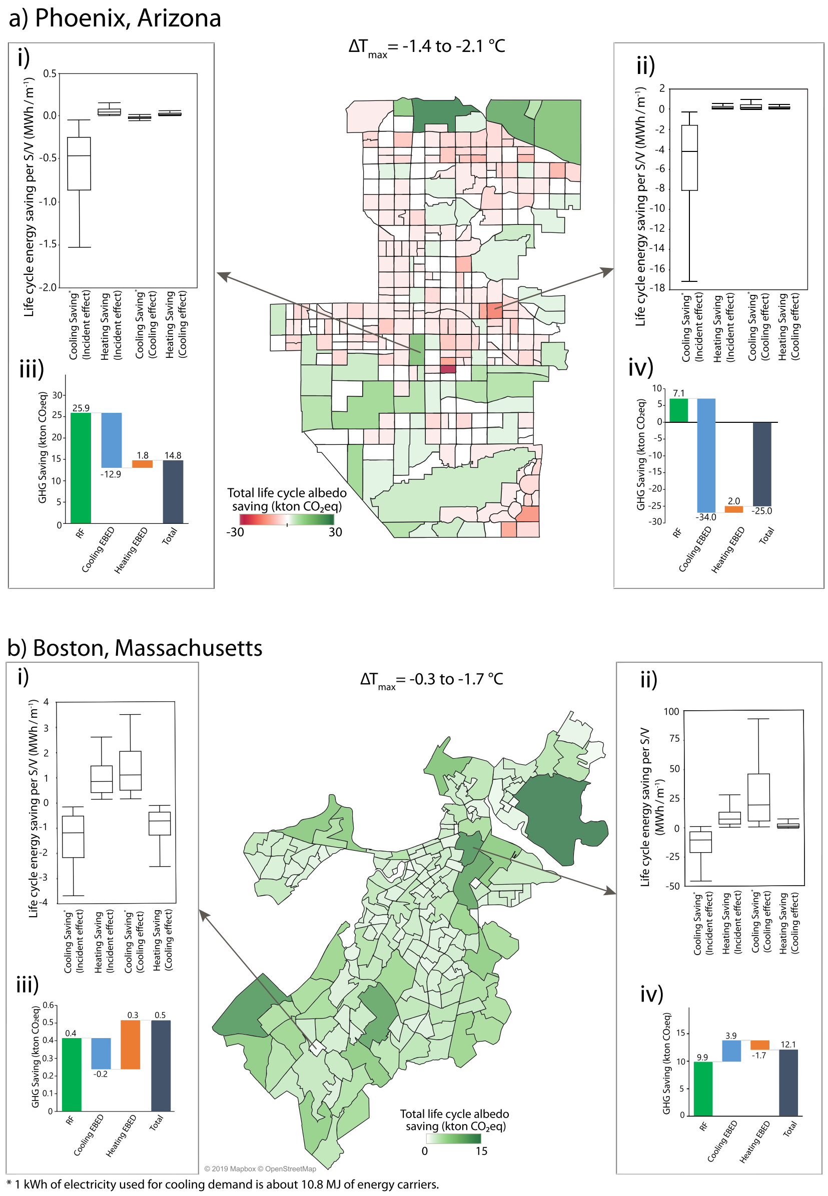

Figure 2. Albedo-induced GHG savings from increasing albedo by shifting from flexible (average 50-year $\alpha = 0.1$) to rigid (average 50-year $\alpha = 0.3$) pavement in the city of (a) Phoenix and (b) Boston shown as a heatmap (negative values imply a burden). Temperature decreases across the cities due to the shift in pavement type are shown above each map. The waterfall charts (iii and iv) represent the disaggregation of the albedo effect in two different neighborhoods within each city, and the box plots (ii and ii) show the contribution of the incident and cooling effect to the total building energy demand in the corresponding census tracts. Note: the scale of the values in the box plots depends on the number of buildings and building stories, and the results are presented for the whole life cycle.

thermal diffusivity), sources of anthropogenic heat (including buildings and traffic), and prevailing regional climate.

The incident radiation effect of pavements on EBED was quantified using a modeling framework developed by the authors and described in ref 37. Because analyzing EBED for each building in a case city is computationally expensive, the framework relies upon neural network metamodels that estimate EBED based on a building's geometry, the local areal density, and the adjacent canyon aspect ratio (building height to street width). These metamodels were built from synthetic data sets derived from the simulation of EBED of thousands of neighborhood configurations executed in coupled-physics models of energy exchange and use within a neighborhood. These models were implemented in the visual programming environment provided in Grasshopper and Rhinoceros 3D. Separate models were constructed for different types of neighborhoods, referred to as local climate zones (LCZs) by Stewart and Oke,[38] within each of the two case cities.

The procedure of assigning the EBED to each building in a case city is presented in the Description of GIS-Based Approach section. The modeling details and framework are presented in the SI document, section S.1.1.2i.

Direct Radiative Forcing. RF is the change in net irradiance at the top of the atmosphere (TOA). Changes in surface albedo induce an RF by perturbing the shortwave radiation budget.[18] For shortwave forcing agents like surface albedo changes, the instantaneous RF at the TOA is linked to surface temperature change and serves as an effective proxy for the stratospheric-adjusted RF at the tropopause.[39] The shading

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effect of buildings and road traffic on pavements can alter the amount of radiation received and the amount of irradiation that will be reflected toward the TOA, thereby altering the RF impact of pavements. The location-specific RF impacts due to changes in pavement albedo were estimated based on a previously developed parametric model. In this model, the albedo-induced RF is a function of the intensity of incoming radiation, atmospheric transmittance, and the change in albedo. Incoming radiation estimates were based on the city coordinates. The input data were taken from the NASA Atmospheric Science Data Center: Surface Meteorology and Solar Energy database.[40] Then, the atmospheric transmittance factors were calculated according to the shading effect of traffic and buildings on the pavements. Modeling details and equations are described in section S1.1.2ii.

Description of GIS-Based Approach. As discussed in the methodology for estimating excess building energy demand, the developed meta-models were assigned to each building based on the neighborhood and building characteristics. The building, pavement, and neighborhood characteristics were collected from several publicly available GIS databases (see section S2.2 in the SI document). Using this information, each building was assigned to a prevailing LCZ and therefore a corresponding meta-model to estimate EBED. The impact of urban morphology on EFC is also manifested in the traffic volume and speed limit. In addition to traffic data, the building dimensions were extracted from street GIS sources, while the density of buildings was calculated using a radial distribution function.[41]

2.4. Case Study. In this study, we evaluated three cool pavement strategies (and one baseline pavement) applied in the cities of Phoenix, Arizona and Boston, Massachusetts in the U.S. These cities were chosen because their climate conditions are quite different. Therefore, the analyses can provide a more comprehensive assessment of the context sensitivity of cool pavement strategies. Previous studies assessed the albedo effect of flexible (asphalt) and rigid (concrete) pavement alternatives.[11] We extend this to include strategies with larger reflectivity values. Specifically, we evaluate rigid, reflective flexible (higher-albedo asphalt), and reflective rigid scenarios as alternatives for the incumbent flexible road network (more than 95% of the road surface in cities are covered with flexible pavements[42]). The average value of rigid pavement albedo was assumed to be 0.3, while for both reflective alternatives, the average value was assumed as 0.4. As the pavement albedo changes as a function of time, we adopted the albedo values and changing rates from previous experimental and analytical studies to capture this dynamic aspect. Details of these assumptions are presented in the SI document, section S1.2. The scenarios were selected as the most practical solutions for increasing pavement construction and reflectivity. A pairwise uncertainty analysis was then performed to capture both the significance (precision) and the effect of size (relevance) of the environmentally preferred scenario. In the modified null hypothesis test method used for the uncertainty analysis, two alternatives are declared to be different only if they exhibit a statistically significant difference of at least some minimum threshold. Following Cohen's guidance for identifying only large effects, we set that threshold to 80% of the standard deviation of the difference.[43] The procedure of the probabilistic analysis is detailed in section S1.4 of the SI document. Because the raw materials to create a reflective rigid pavement are not available in a large capacity in all markets, we also explored the implication of having only reflective flexible and rigid alternatives available. As the role of carbonation and lighting was trivial compared to the total life cycle impacts, they were excluded from the scope of this study.

3. RESULTS

The impact of cool pavement strategies on both UHI and GCC in Boston and Phoenix is presented for three scenarios that involve shifting from flexible (the dominant pavement type in these cities, with an average albedo of 0.1) to (1) conventional rigid (which has a higher average albedo of 0.3), (2) reflective flexible (average albedo of 0.4), or (3) more reflective rigid pavements (with an albedo value similar to that of reflective flexible). To better characterize the implications of pavement material change, we explore use-phase implications individually, then present the complete life-cycle result. First, a detailed assessment of albedo-induced impacts of pavements is presented from two perspectives: the contribution of incident radiation and of cooling ambient temperatures on EBED and, at a higher level, the intensity of RF and EBED impacts in different neighborhoods. A detailed exploration of the impact of pavement selection on vehicle emissions, including the relative contribution due to roughness and stiffness, is presented in the SI document, Figures S11 and S12. Then, the potential life cycle GHG emissions of the four pavement options are presented. Finally, considering the existing uncertainty in the parameters, the lowest-impact scenario(s) for each neighborhood are identified and presented.

3.1. Albedo-Induced Temperature and Climate Effects of Shifting to Cool Pavements. The choropleth maps in Figure 2 represent the albedo-induced (only) GCC effects of shifting from the existing flexible (albedo of 0.1) to conventional rigid pavements (albedo of 0.3), aggregated at the census tract (also referred to here as "neighborhood") level, for both Phoenix (a) and Boston (b). Figure 2 also includes detailed breakdowns of albedo-related results for two illustrative census tracts in each city (inset bar plots). Decreases in modeled peak summer temperature across the census tracts within each city are noted above each map ranging from 0.3 to 1.7 °C in Boston and 1.4 to 2.1 °C in Phoenix. The average temperature changes in different LCZs can vary significantly depending on the neighborhood morphology characteristics (Figure S8 in the SI document). The average temperature reductions are 4 times smaller than the peak summer temperature reduction. Denser neighborhoods result in a slighter temperature change during different hours of days and nights compared to sparsely built neighborhoods (e.g., LCZ 9) as the buildings can likely obscure the incoming solar radiation, and therefore, there is a lower chance of temperature change as a result of pavement albedo modification. For any given morphology, the temperature changes in Phoenix are more pronounced and are more than double what is simulated for Boston. Interestingly, shifting from flexible to rigid pavement can slightly increase the night hour temperature, which implies the importance of materials properties, but the daylight temperature reduction is more pronounced when using rigid pavement compared to reflective coating (albedo of 0.4; Figure S9 in the SI documents). These findings are supported by prior research. An experimental investigation by Li et al. found similar changes at day and night hours.[44] Additionally, the average and peak temperature findings are within the range of 15 reflective cases

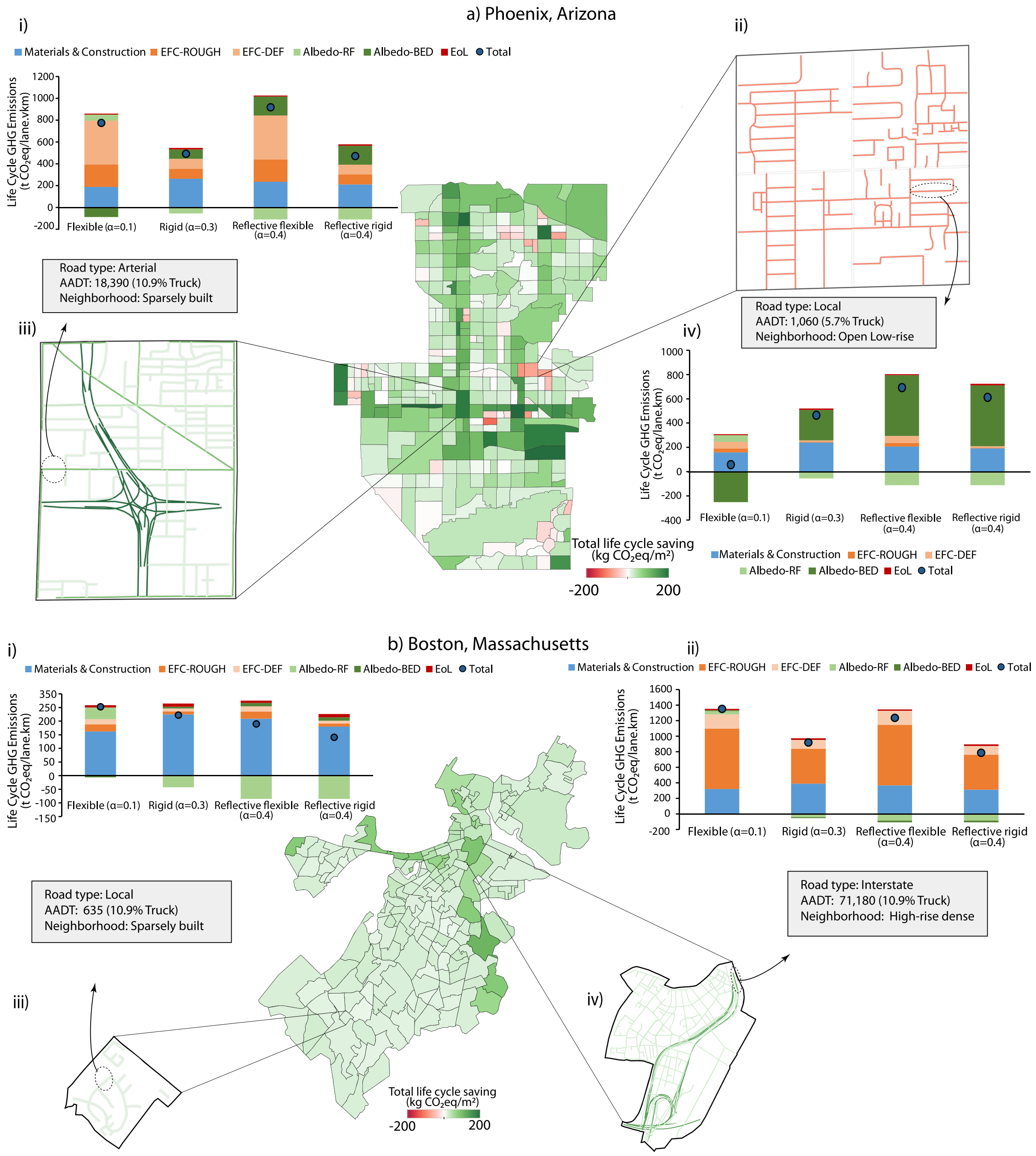

Figure 3. Total life cycle global warming potential savings of shifting from flexible (average 50-year α = 0.1) to rigid (average 50-year α = 0.3) pavements in the cities of (a) Phoenix and (b) Boston on the heatmap (a negative number indicates a burden). The bar charts (i and iv for a and i and ii for b) represent the potential life cycle GHG emissions and breakdown of those emissions associated with flexible, rigid, and higher reflective scenarios for the specified road segments in the map (ii and iii for a and iii and iv for b). AADT = average annual daily traffic.

(0.3−2.5 °C peak temperature reduction and 0.1−0.5 °C average temperature reduction) that Wang et al. reviewed.[45]

The predominant local climate zone (LCZ) for each census tract in Boston and Phoenix is presented in the SI document, Figure S6. In all neighborhoods, the RF effect from albedo change leads to a GCC benefit (negative RF). In the neighborhoods where the surface area of pavements is relatively larger than that of buildings, the benefit from the RF effect dominates the EBED results (e.g., compare the green bar (RF) in Figure 2a.iii and b.iv with the light blue (cooling EBED) and orange (heating EBED) bars in the same panels). Therefore, we observe a net GCC benefit induced by the albedo increase alone in those regions.

Unlike the RF effect, the impact of albedo change on EBED varies greatly by context. In Boston, an albedo increase reduces EBED as often as it increases it (52% of census tracts see a reduction, see Figure S8a). Some neighborhoods may experience an increase in cooling EBED (negative savings, light blue bar) and a decrease in heating EBED (orange bar, see Figure 2b.iii) or vice versa (Figure 2b.iv). This occurs because, in Boston, the cooling and heating loads induced by pavement albedo are all on the same order of magnitude (Figure 2b.i and ii). As such, the net balance of these effects

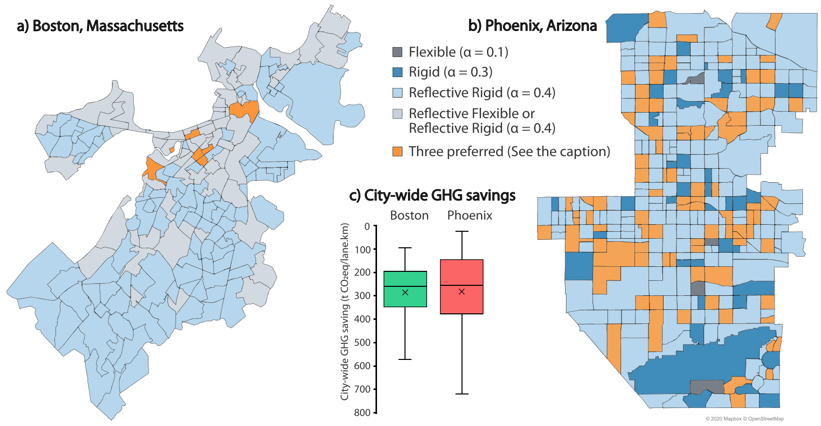

Figure 4. Environmentally preferred scenario(s) (lowest life cycle GWP) considering the uncertainty and variability sources in the LCA of pavements in (a) Boston and (b) Phoenix. The difference in mean GWP impact of the most preferred scenario and others is more than 0.8 standard error units. In cases where this difference threshold is not meant, there is a statistical tie among the alternatives. In Boston, the tie is among reflective flexible, reflective rigid, and rigid. In Phoenix, the statistical tie is among flexible, rigid, and reflective flexible. (c) Potential city-wide GHG savings obtained from shifting to the most preferred scenario. The ends of the box are the 25th and 75th percentiles. The median is marked by a horizontal line inside the box. The mean is marked by an "x." The whiskers are the two lines outside the box that extend to the minimum and maximum values.

varies widely across the city depending on the local morphology. Nevertheless, adding the beneficial impact of RF (Figure 2b.iii and iv) to the varying EBED impacts in Boston results in a consistent GCC benefit due to just albedo change across the neighborhoods in Boston.

Trends within Phoenix are quite different than those in Boston. As shown in Figure 2a, the range of its temperature reduction is larger than that in Boston. This result is in line with Manoli et al.[46] that showed that surface albedo increases alleviate the intensity of UHIs more effectively in dry regions. Despite this ambient cooling, the incident radiation-induced cooling burden is consistently larger than that of other EBED effects in Phoenix (compare first box-and-whisker with others in Figure 2a.i and ii). This results in a net GWP burden associated with EBED in most Phoenix census tracts (see Figure S8c for the EBED results of all CTs). As shown in Figure 2a.iii and iv, however, once RF benefits are considered, the total GWP implications of albedo change (only) vary considerably across Phoenix CTs. Generally, neighborhoods with a high ratio of paved surface area to built volume tend to show benefits in Phoenix.

3.2. Pavement Life Cycle Global Warming Potential Impacts of Shifting to Cool Pavements. The choropleth maps in Figure 3a and b represent the life cycle GCC benefit (or burden) measured as GWP savings (or burden, kg CO_2e/m^2) of shifting from the existing flexible to a rigid pavement for each census tract in the cities of Phoenix and Boston, respectively. This result differs from that shown in Figure 2 because Figure 3 results include the impact of other life-cycle stages. Breakdowns of lifecycle GWP by lifecycle stage associated with both pavement designs along with two higher albedo scenarios (reflective flexible and reflective rigid) are shown as stacked bar plots for selected road segments in each city (Figure 3a.i and iv and b.i and ii).

The first notable feature of these maps is that results can vary widely across census tracts within each city, reinforcing the importance of high-resolution modeling. For the city of Phoenix, most census tracts (68%) would benefit from replacing flexible pavements with rigid ones, but the implications range widely from a benefit of 1400 t CO_2e to a burden of 1100 t CO_2e per lane·km. These benefits are largest where traffic volumes are high. Deflection-induced excess fuel consumption (DEF-EFC) can be quite large in Phoenix because of the impact of high ambient temperatures on the viscoelastic properties of flexible pavements. In Phoenix (see Figure S11), the magnitude of the EFC benefit alone exceeds the added embodied burden for rigid pavements in 97% of road lane-km (21% in Boston). For Phoenix neighborhoods where both albedo-related effects result in a net burden (red-colored census tracts in Figure 2a) and traffic volumes are low, replacement of flexible pavements would lead to a GWP burden (red-colored choropleths in Figure 3a). In fact, as illustrated in Figure 3a.ii and iv, in these neighborhoods, all higher albedo alternatives (rigid, reflective flexible (flexible with reflective coating), and reflective rigid pavement) lead to a GWP burden.

For the city of Boston, although results also range from a benefit of 640 t CO_2e to a burden of 40 t CO_2e per lane·km, their strategic implications are uniform: rigid, reflective flexible, and reflect rigid scenarios (Figure 3b.i and iii) lead to lower life cycle GWP impacts than a flexible pavement in all CTs. The segment-level results of shifting from flexible to different cool pavement strategies are provided in the interactive Dashboard of Boston and Phoenix associated with this paper.[47,48] These results represent mean impacts. The next section will explore the impact of uncertainty.

3.3. Comparative Analysis of All Pavement Alternatives Considering Uncertainty. There are several sources of uncertainty and variability in any LCA analysis. These sources include but are not limited to the data quality of inventory, input parameter variability (e.g., the inherent variations in the world), and modeling choices.[49,50] We account for these sources in a probabilistic LCA (see SI Spreadsheet) in the comparative analysis of four pavement alternatives and then we implement a modified *t* test method[43] to identify alternatives with statistically significant lower implications of climate change impact, or if there is a statistical tie (SI section S1.4). The modified *t* test identifies an alternative as preferred only if it exhibits a statistically significant difference that exceeds a prescribed threshold. For

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this analysis, the threshold was set to 80% of the standard deviation of the difference, a level recommended by Cohen[43] to identify a difference only when large effects are present. Significance was evaluated at the 0.05 level.

As shown in Figure 4a and b, the probabilistic results present a more nuanced picture of the lowest-impact alternative among the four investigated pavement types in many CTs. Of the four scenarios tested, the reflective rigid pavement (lightest blue color census tracts in Figure 4) is the most frequently preferred in both cities (53% of lane·km in Boston, 73% in Phoenix). In Boston, these results indicate that replacing conventional flexible pavements with a higher albedo alternative is always the best choice (reflective rigid preferred in 53% of lane·km; reflective rigid or reflective flexible in 45% lane·km; and rigid, reflective rigid, or reflective flexible in 2%). In Phoenix, the results are more diverse, but rigidity appears to be the most pervasive driver of change with rigid solutions being the clearly preferred alternative in 82% of lane·km (73% reflective rigid and 9% rigid). For the rest of Phoenix, there are 1% of lane·km where no change is the best alternative and 17% where there is not a sufficiently large effect difference to resolve among no change (flexible), rigid, and reflective rigid alternatives. For these specific locations, a refining process on the data uncertainty should be applied to reduce the noise.

Considering the most environmentally preferred scenario across all segments, results indicate an average savings of 285 t CO_2eq savings per lane·km in Boston and 280 t CO_2eq savings per lane·km in Phoenix (see Figure 4c) by shifting from the traditional technology to the preferred cool pavement strategy.

Generally, shifting from a flexible to rigid alternative results in a larger GCC benefit in high-volume roads (see SI, Figure S9). Therefore, in those census tracts that mostly possess arterials and interstates, the climate change impact of the scenarios is distinguished enough that the preferred alternatives cannot be obscured by the introduced uncertainty to the system. While this statement is true for both Phoenix and Boston high-volume roads, the savings intensity per lane·km on low-volume roads follows different intensity levels depending on their context. In Phoenix, the low-traffic roads that are located in sparsely built neighborhoods receive larger savings. On the other hand, the dense neighborhood local roads would experience a minimal GCC savings from the most preferred scenario as the EBED burden is large enough to neutralize the expected savings in the embodied, RF, and PVI in the alternative scenarios. In Boston, low-volume roads located in dense areas experience larger GCC savings (i.e., more significant EBED benefits) than those located in sparsely built areas.

4. DISCUSSION

As more than 95% of the GHG emissions in urban areas are attributed to building and vehicle operation, several strategies have been proposed to reduce or offset these emissions.[51] Many of these strategies require actions by systems outside the control of city decision makers (e.g., grid decarbonization) or behavior change on the part of citizens. These challenges make it difficult for cities to implement GHG mitigation solutions.[52] Pavement material change is one strategy that cities have a strong influence over (if not total control).

The modeling approach presented in this study has provided insight into the climate change impacts of cool pavement strategies (the global warming potential induced by different reflective pavement solutions). Considering the uncertainty and variability (fifth and 95th percentile values) and assuming a 10-year period for reconstructing/repairing the whole area of the urban road network, the selection of the lowest-impact cool pavement strategy can offset 0.9−3.1 Mt CO_2eq from the city of Boston over a 50-year period. That is the equivalent of removing the emissions of driving 5500 to 17 800 vehicles over that same 50-year period. The savings range for Phoenix is much larger at 2.2−16.7 Mt CO_2eq over 50 years (given the 2.3 times and 4.6 times larger population and road length, respectively), the equivalent of emission from 13 700 to 96 000 vehicles.

Considering Boston's GHG reduction pledge of carbon neutrality by 2050,[53] cool pavement strategies can offset 1.0−3.0% of the total GHG emissions in the next 50 years. Considering Phoenix's net-zero goal by 2060,[54] the potential GHG savings from implementing the lowest-impact cool pavements can offset 0.7−6.0% of the total GHG emissions of the city during the next 50 years. Although these percentages are not large, they can be realized with little marginal investment by simply selecting appropriate pavement materials during the next major maintenance of a given roadway.

Globally there are around 4 billion km^2 of urban area.[55] Even if only 7.5% of that area is paved (this ratio is 7.7% in Phoenix, 15% in Boston), then the estimated potential GHG savings suggests that making the appropriate pavement material choice could lead to a global reduction in the impact of 5.0 to 44.7 Gt CO_2e saved in the next 50 years. This value range corresponds to the fifth and 95th percentiles of the values shown in Figure 4c.

This research also clearly showed the importance of having a high-resolution tool that can capture the impact of heterogeneity across urban neighborhoods to identify the preferred pavement alternative. Traffic, city morphology, and pavement materials interact to determine the pavement's impact on urban air temperatures and climate. These effects vary widely across a city.

There are opportunities to further improve the potential GHG savings from cool pavement strategies. Harmonizing the building envelope characteristics with pavement albedo may intensify the potential GHG savings. For example, particularly in warm cities like Phoenix, increasing the building envelope albedo would reflect a larger amount of incident radiation, reducing the amount of energy absorbed by the building. By contrast, to accentuate the heating savings expected from the albedo increase in cold cities like Boston, a darker color envelope would further reduce the EBED in winter. Also, the emission factors of cooling and heating energy can significantly and directly change the results. More intensive grid decarbonization can extend the potential GHG benefits resulting from cool pavement strategies in warm climates like Phoenix. Further study is required to assess the effect of reflective pavement applications on other life cycle impact categories. The analysis of other impact categories can comprehensively reveal the environmental repercussions of reflective pavement strategies. Moreover, the effectiveness of cool pavement decisions made for these cities under the presented framework should be considered within the context of the budgetary constraints of the asset management plans for each city. In the end, the results presented here suggest there are many opportunities for cool pavements to mitigate both UHI and GCC impacts. The framework described should allow cities to identify those opportunities in a computationally efficient manner. The validation and accuracy of these models have

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been studied by several researchers. Nevertheless, there is an opportunity for further studies to evaluate the overall uncertainty when the models are jointly used.

Finally, every pavement type selection decision will be a balance between performance (including function, construction, and maintenance), economic (including initial and life cycle costs), and environmental (including life cycle and local impacts) factors. Our approach demonstrates how to compare the life cycle environmental impacts of pavement designs while accounting for uncertainty among the alternatives. Figure 4 shows how we can comment on the statistical significance of the difference between alternatives. However, making decisions that consider performance, economic, and environmental factors requires a multiattribute utility analysis that includes weighting among the factors. We added this clarification to section 3.3 of the manuscript.

ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acs.est.1c00664.

Details of calculations and case study methodology specifications (PDF)

Parameters, probability distributions, and statistical values as well as pavement design details and performance (XLSX)

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Notes

The authors declare no competing financial interest.

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