2020

ADVANCING THE INSTALLATION OF "COOLER" ROADWAYS

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1. Executive Summary

The Global Cool Cities Alliance (GCCA) is a non-profit organization focused on accelerating a global transition to cooler, healthier cities through increasing the solar reflectance of urban surfaces. In early 2020, GCCA launched the “Cool Roadways Partnership”, an initiative with manufacturers, public works officials, and sustainability directors across the U.S. to initiate cool roadway pilot projects to mitigate the urban heat island (UHI) effect. While pavements are a significant part of the strategy to build heat resilience against UHI effect, there are a number of barriers to getting cool pavement solutions to scale, specifically for roadways. A majority of these barriers can be solved through the implementation of cool pavement projects in more cities. However, cities may struggle to identify and prioritize suitable pilot locations that will provide the greatest benefit, especially in reducing the adverse health impacts of extreme heat.

The interest in cool pavements is growing. The “Cool Roadways Partnership” initiative originally started with 3 cities as signatories to a Request for Interest (RFI) that indicates their desire to install cool roadways. This has grown to 19 cities across the U.S. with an expectation that over 25,000 lane miles will be repaved and over $2 billion will be spent over the next decade. Currently, all 19 cities signed to the Cool Roadways Partnership are spending approximately $460 million dollars a year to repair and/or replace 5,500 miles of roads each year.

This report was written by a team of Master of Science in Sustainability Management students working as a Capstone consultancy at Columbia University. This report details the team’s methodology, findings, and recommendations, featuring a screening toolkit to identify pilot project locations and a cost-benefit analysis of implementing cool pavements. This screening toolkit helps cities to prioritize social equity and health outcomes of implementing cool pavements while layering technical realities. The screening toolkit includes a checklist of priority parameters for prospective cities to use when identifying pilot project locations and, where possible, recommendations for alternative options when priority parameters are not available.

To form the team’s recommendations, they performed a review of existing research, popular media, cool roadways case studies, and conducted a comparative analysis between each of the cities involved in the roadway partnership to preview local policy, economic, and physical conditions. The team also interviewed experts including sustainability directors, public works officials, manufacturing representatives, and heat vulnerability specialists. This initial review guided the team's design of a screening toolkit. The toolkit includes an instructional guide and methodology for comparing different locations within a city, and a cost benefit analysis to measure the project's impact. Finally, the team partnered with city representatives from San Antonio, Texas to pilot the toolkit, obtain feedback, and implement recommendations. The team incorporated political insight from San Antonio to identify which districts would be most willing to implement a cool pavement project. After using this information as a feasibility indicator, alongside a site's environmental and social scores, five census tracts were identified as potential cool pavement pilot locations.

By developing this framework for cities to find locations and garner support for cool roadway projects, the demonstration siting process will help GCCA attain its goal of accelerating a global transition to cooler, healthier cities through increasing solar reflectance.

This methodology created by the team can be replicated for future pilot projects globally. In this way, the team has provided GCCA and prospective cities with a replicable process that can ease the implementation of a cool pavement solution to build heat resilience across the globe for years to come.

2. Introduction and Context

2.1 Project Scope

At the request of the Global Cool Cities Alliance (GCCA), the Capstone team was tasked with developing a prioritization tool based on equity and community health that GCCA and its partners will use to identify cool roadway pilot locations across the country.

2.2 Urban Heat Island Effect and the Demand for Cool Roadways

The Urban Heat Island (UHI) effect is an environmental phenomenon that results in temperatures within cities to become significantly warmer than the surroundings areas. As cities replace vegetation with buildings, roadways, and other structures to accommodate growing populations, these surfaces absorb the heat causing an increase in surface temperature among other effects. Higher temperatures are associated with increased energy consumption, compromised human health and comfort, an increase in air pollutants and greenhouse gases, and compromised water quality.[1]

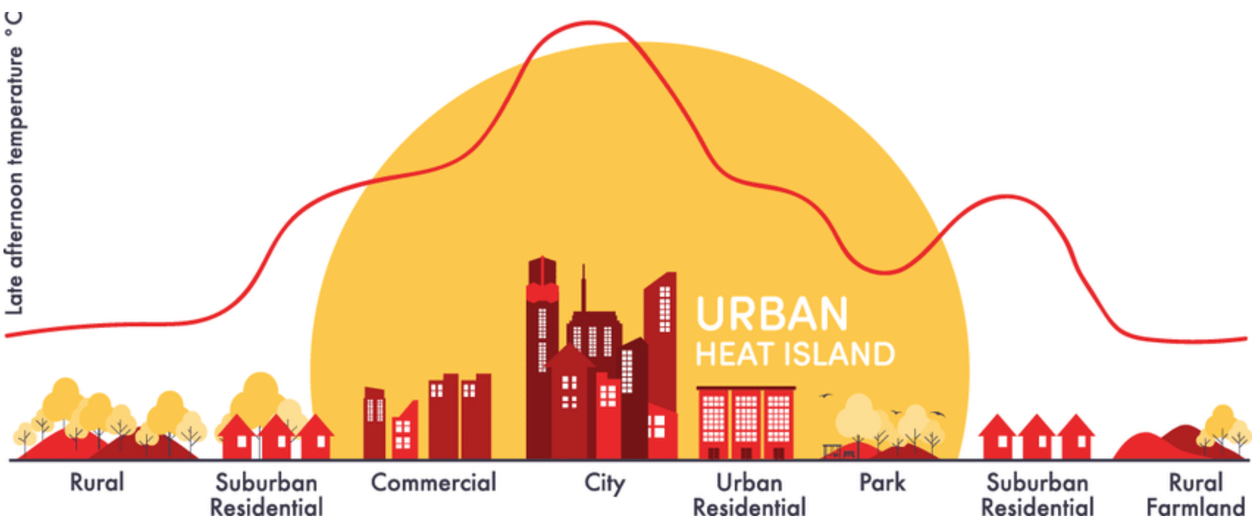

Figure 1: Diagram of Urban Heat Island Effect.[2]

As pavement makes up 30% of a city's surface on average, implementing cool roadway solutions will play an important role in improving a city's heat resilience.[3] The 19 cities within the Cool Roadways Partnership have expressed their interest in pursuing cool pavement solutions or have already made progress on including them as part of their urban heat resiliency efforts. While some cool pavement technologies exist, there is a lack of awareness of the products and benefits as well as a lack of knowledge of the local effects and performance of cool pavement solutions. This is due in large part to the very small number of existing pilots that could influence innovation from manufacturers and ease implementation for cities.

Another part of the challenge for cities, is prioritizing pilot locations for a cool pavement solution that will provide the greatest benefits with respect to reducing heat in combination with protecting vulnerable communities. Urban heat negatively impacts air quality and health of community residents, especially low-income and marginalized communities as they tend to be the hottest and most paved areas in the city.[4] A 2020 study found that formerly redlined neighborhoods, which are generally low-income and majority Black, are on average 5 degrees hotter in summer than areas favored for housing loans. In some cases, the difference is as large as 12 degrees.[5] [6] This disparity in heat leads to excessive mortality, more hospital admissions, higher energy usage, and economic labor productivity loss.[7] It is therefore essential to take an equity-informed approach to UHI mitigation strategies. By reducing air temperatures, cool pavement technologies can improve the quality of life for residents and address heat-related inequality.

2.3 UHI Mitigation Efforts

Existing UHI mitigation strategies include cool roofs, cool pavements, green roofs, smart growth, and vegetation. The table below includes a brief explanation of each of these mitigation strategies.

Mitigation Type	Strategy
Cool Roofs & Walls	Installing roofs and vertical surfaces made of materials or coatings that reflect more sunlight and shed heat more efficiently
Cool Pavements	Installing paving materials on sidewalks, parking lots and streets by reflecting solar energy and/or enhancing evaporation
Green Roofs & Walls	Growing a vegetative layer on a rooftop or vertical surface to reduce surface roof temperature
Smart Growth	A range of development and conservation strategies that protect the natural environment
Trees and Vegetation	Using tree and vegetation cover to lower surface and air temperatures by providing shade and cooling effects

Table 1: Description of UHI mitigation.[8]

2.4 Cool Pavement Types and Benefits

There are two types of cool pavements: reflective and permeable. The objective of a cool pavement is to increase surface albedo or enhance evaporation. Albedo is the portion of solar radiation that is reflected from a surface versus absorbed by the surface. Thus, a surface with greater albedo under solar radiation will be cooler. Reflective pavements have a light-colored, high solar reflectance finish resulting in an increased albedo effect.[9] There are two subsets of permeable pavements: porous and pervious. Both pervious and porous pavements decrease surface temperature through evaporation.[10] However, porous pavements allow water to drain through the surface layer to replenish the water basin whereas pervious pavements allow for water to percolate along the surface.[11]

3. Methodology

3.1 Review of Cool Roadway Partner Cities

First, the team conducted background research of cities that signed the RFI, and then consulted with key stakeholders to better understand how to develop the screening toolkit. As the list of RFI cities expanded from 3 to 19 at the start of our research, it was important for the team to get an idea of each city's suitability for pilot project implementation based on a variety of both quantitative and qualitative factors. These factors were determined based on the team's research of previous cool pavement pilot projects as well as discussions with the GCCA. The table below lists the factors that the team utilized to evaluate RFI cities.

Quantitative Factors	Qualitative Factors
Average surface temperature	Carbon reduction goals
Average energy consumption	Carbon reduction policies
Current air quality	Equity policies
Pavement statistics: material	Energy goals
Pavement statistics: area	Air quality standards
Pavement statistics: maintenance	Suggested locations for UHI reduction
Pavement statistics: vegetation type	
Socio-demographic distribution	
Geographical factors	

Table 2: Quantitative and qualitative factors used to evaluate RFI city suitability for pilot projects

3.2 Participant Research and Surveys

The team identified three categories of stakeholders to gather more insight from including cool pavement product manufacturers, city representatives, and specialists in urban heat island effect.

Cool Pavement Product Manufacturers: The team consulted cool pavement manufacturers, including GuardTop and Petrochem Materials Innovation (PMI), to understand their product technologies as well as their acquired knowledge from implementing their technologies in different cities.

GuardTop offers a reflective asphaltic coating product called CoolSeal that is designed to achieve lower surface temperatures through its color and reflectivity.[12] Another manufacturer, PMI, produces a Central Mix REAS (Rubberized Emulsion Aggregate Slurry) which is a slurry seal that helps to extend the life of structurally sound pavements.[13]

In interviews with these manufacturers, the team learned that many cities are excited about these solutions but are primarily concerned with the upfront costs and social factors such as equity and community health. Both manufacturers emphasized that budgeting drives the implementation process and that it is important to create a demonstration site in cities so that officials can evaluate the costs and benefits directly. To do so, it is important to focus on benefits related to equity and community health as well as highlight the increased pavement longevity that these solutions provide.[14] [15] The complete list of questions that were asked to the manufacturers can be found in Appendix A.

City Representatives: The team developed a survey that was sent to all 19 Cool Roadway Partner cities in order to collect data on a city's interest in piloting a cool pavement technology, availability of data related to urban heat island effect, bandwidth to work on a cool pavement pilot project and current efforts in heat mitigation. Out of the 19 cities that the survey was sent to, the team received 14 responses from a mix of sustainability and public works officials. The complete list of survey questions can be found in Appendix B.

The results from the survey revealed that for city representatives, the greatest concerns of implementing a cool roadway solution are the upfront costs and costs of maintenance. In regard to UHI mitigation, the top three concerns for implementing a cool pavement were 1) reducing surface temperature, 2) climate response and, 3) health issues. Lastly, the team found that the majority of cities that responded had already completed studies in surface temperature, air quality, and heat vulnerability.

Additionally, the Capstone team met with city representatives from San Antonio and the San Antonio Water Authority as they expressed interest in testing an iteration of the toolkit. Conversations with San Antonio representatives helped the team to further refine the parameters that were important to this city when identifying a pilot location. The parameters discussed included water quality, air temperature, flood likelihood of an area and political willingness. The list of questions that were asked to city representatives can be found in Appendix C.

Academia/Experts: A mapping technician, Garrett Riha, was also consulted to gather insight into his work developing an index to rank San Antonio's various neighborhoods by priority of need for UHI mitigation solutions. He helped guide the team's approach to include heat and social parameters in developing the tool. Additionally, he advised the team on where to source data that would be a necessary component of the final deliverable.[16] This also informed the team's decision to develop an index for cool pavement pilot locations.

3.3 Case Studies and Lessons Learned

The team examined case studies of various cities throughout the world that have successfully implemented, or are in the process of implementing, cool roadway pilot projects. By analyzing 7 cities' approaches to implementing cool roadway solutions, the team was able to gather relevant information for the development of future pilot projects in the Cool Roadway Partner cities. The table below contains the cities that provided the team with relevant information and best practices learned from each of them.

Cities	Best Practices
Tokyo, Japan	● Tokyo implemented 96km of reflective coatings and 20km of permeable pavements.[17] ● Permeable pavements can serve as an effective method to reduce the UHI effect as well as play an important role in a city's stormwater management strategy. ● A thermal barrier coating can reduce surface temperature by as much as 46°F when compared to standard asphalt pavement. ● Water-retentive pavements can suppress the temperature rise of road surfaces by as much as 50°F through water evaporation.[18]
Los Angeles, California	● As of 2018, Los Angeles installed $13,000m^2$ of cool pavement in 15 locations.[19] ● Combining a cool pavement with trees and shade structures can effectively amplify the reduction of the UHI effect. ● It was found that summer afternoons in Los Angeles, cool pavement was 10-15°F cooler than nearby asphalt.[20]
Fresno, California	● Fresno modified $18km^2$ of pavement with cool pavement technologies. ● It was found that depending on time of day and season, the city's cool pavement reduced air temperature between 32.07 and 32.18°F.[21]
Chula Vista, California	● Effective UHI reduction technologies identified by the city included porous pavements, rubberized pavements, vegetated and non-vegetated pavers, various surface treatments, and shade trees.[22]

Table 3: Cool pavement case study cities and best practices learned from each

3.4 Resulting Approach

Upon finalizing the literature and stakeholder review, the team outlined the key components to be included in the final tool. First, the team determined that partnering with one to two cities would create diversity in range of feedback and help to further refine the tool. Second, urban heat and social parameters would be included when screening pilot locations within a city. Third, the team planned to address the monetized benefits of implementing a cool roadway technology into the tool based on feedback from manufacturers and survey responses from city representatives. These three key components outlined the approach and next step of tool development.

3.5 Cool Pavement Screening Process

This section will introduce the screening toolkit that the team has developed for GCCA and cities interested in implementing cool pavement solutions. The purpose of the toolkit is to help city governments identify specific areas in their jurisdiction that would provide health, equity and cost benefits from cool pavement coating installations. Before the screening toolkit can be used, a city must also be screened for pilot project suitability, which will be elaborated on in the following subsection.

3.5.1 Prior Selection of Cities for Pilot Project

Prior to the use of the screening toolkit, the team identified the most suitable cities for the pilot development of cool roadways. Two cities were selected based on four key criteria of their availability of data and resources, willingness and interest to participate, range of geographical diversity, and size of the city.

The most important criteria the team used for selecting pilot cities was to ensure that they had sufficient **data and resources** for the tool. This also indicated what data the cities needed and gave them ample time for preparation. Cities were also evaluated based on their **willingness and interest to participate** actively and in a timely fashion. Additionally, pilot cities were selected based on the need for **geographical diversity** in the pilot project implementation. This was to ensure that the pilot covers a range of geographical attributes and settings, which in turn can provide diverse examples should other cities want to implement cool roadways in the future. Another factor considered was the **size of the city**. A mix of small, medium, and larger cities would help future pilot locations determine similar sizing factors in their implementation.

3.5.2 Criteria for Neighborhood Selection

The main component of the toolkit is a set of criteria for selecting a pilot neighborhood or areas within the city that would deliver the greatest environmental and social benefits. The creation of these criteria began with a collation of various parameters the team came across in their research, industry review, and precedent studies. The result of this analysis was an extensive list of parameters used to assess UHI intensity, and its effects in Figure 2. The team narrowed down the list and chose 6 key parameters to form concise criteria that would be helpful for the client and cities. This decision-making process was informed by precedent and insight from manufacturers that worked on successful pilot projects in Phoenix and LA.

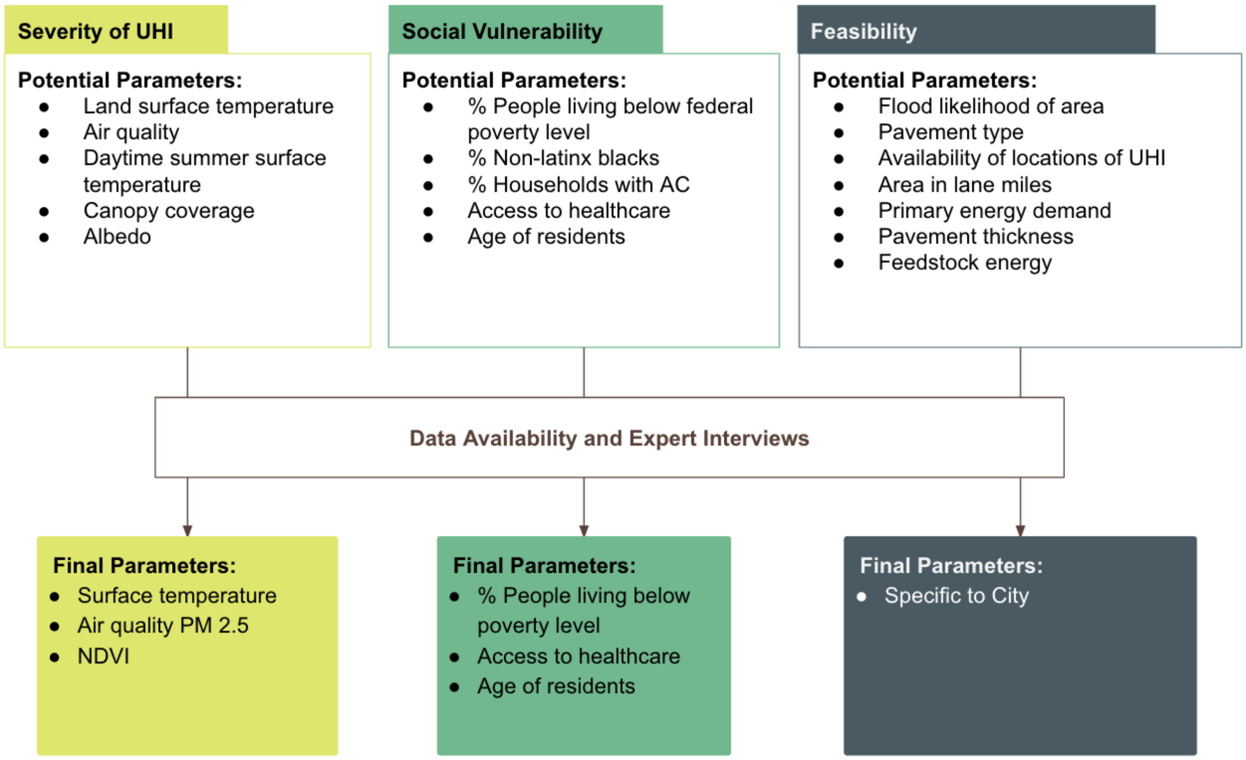

Figure 2: Initial parameters and the final list of parameters chosen for neighborhood selection.

Based on the initial research of UHI impacts and cool pavement implementation, the team decided that the criteria used to assess different neighborhoods needs to be holistic and consider three important factors: the intensity of local surface UHI, the social vulnerability to extreme heat of the people living near the pilot site, and feasibility of implementation. Previous studies of heat risk factors suggest mapping sociodemographic variables (i.e. vulnerability, population density, community health) from census data to provide an indication of the spatial variation in vulnerability, as well as to contribute to research on equity improvement and tackling heat-vulnerability issues.[23] [24] [25] This approach, however, does not account for physical environment variables that may contribute to increased risk from extreme heat events. For example, vulnerable residents living in an area of low environmental heat load may be less at risk than a group living in an area of high heat load. Accounting for the influence of social and environmental factors on residents' vulnerability to extreme heat events may support improved planning and intervention strategies.[26] Thus, the team chose parameters that would help to analyze neighborhoods based on this holistic framework that accounts for social and environmental factors concurrently.

a. Parameters for Determining the Severity of the Urban Heat Island Effect in Target Cities

Surface Temperature

The land surface temperature (LST) is a crucial indicator of UHI because it can be directly used to determine heat exposure and is also more readily available than air temperature data.[27] It represents the heat energy emitted by the land, infrastructure, buildings, and other surfaces.[28] Often, the surface UHI phenomenon is indicated by land surface temperature differences in areas, especially between lesser and more developed urban areas.[29] The measurement of surface UHI effect using the land surface temperature difference between the city and the surrounding region is able to accurately reflect the intensity of the urban heat phenomenon.[30] Using Landsat Provisional Surface Temperature (LSAT) as a measurement is particularly useful for UHI studies.[31] Hence, the team chose surface temperatures as the most accurate and direct indicator of the cool roadway implementations.

Air Quality

Air quality is a chosen parameter for the tool as it is closely influenced by changes in urban heat levels, air quality, and ground level ozone. Hotter temperatures raise the demand for electricity, resulting in the likely reliance on fossil fuel-based power plants to meet much of this demand, leading to an increase in air pollutants and greenhouse gas emissions. The heightened energy demand can increase harmful air pollutants such as, ground-level ozone (or smog), fine particulate matter, and even acid rain.[32] Urban heat can be reduced through urban greening, which also decreases average ozone concentrations.[33] As temperatures increase, the heat and sunlight combine with chemical compounds and nitrogen oxide emissions, creating a smog of ground-level ozone gas.[34]

Normalized Difference Vegetation Index (NDVI)

NDVI refers to the state of plant health, based on how the plant reflects lights at certain frequencies.[35] It is mainly used to quantify vegetation greenness and can be useful in helping to understand vegetation density and changes in plant health.[36] This is an important parameter as it provides direct information on the extent and composition of vegetation cover.[37] NDVI can be used to determine the canopy coverage in an area, which in itself is a popular and effective method to mitigate UHI effects, often present in a city's green targets and long-term climate action plans. Increasing canopy cover can effectively reduce temperatures and can be an indicator for cities to compare heat in areas with different canopy coverages.[38] Green spaces in a community can decrease the risk of heat-related illnesses and fatalities, and urban areas with lesser impervious cover or greenery might be more prone to such incidences.[39] Studies in India and China have found that higher vegetation or rural areas recorded lower temperatures when compared to built-up areas.[40] [41] Overall, there was a negative correlation between land surface temperature and NDVI, indicating that green areas can weaken the UHI effect, whilst a positive correlation between the land surface temperature and lesser vegetation can strengthen the effect of UHI.[42] Thus, it is important to consider that if an area already has a high amount of shading from trees, this might decrease the benefits achieved from high albedo surfaces, and may not be the optimal location for a pilot project.[43]

Albedo/Solar Reflectance

An additional parameter consideration is albedo, which is a measurement of how much light that hits a surface is reflected without being absorbed (NCSU). Albedo is found to be closely related to the benefits of cool pavements and temperature reductions in urban areas. Increasing urban albedo with highly reflective materials can help maintain lower surface temperatures, presenting an effective solution to mitigate UHI.[44] In the greater Los Angeles area, a study attributed over $90 million annually in savings from temperature reductions from increased pavement albedo.[45] As pavement albedo increases, cooler temperatures slow the rate of ozone and smog formation and reduce evaporative emissions from vehicles, ultimately achieving massive reductions in carbon dioxide emissions and costs.[46]

b. Parameters for Social Vulnerability

Incorporating data from different perspectives results in a richer and more robust assessment of vulnerability when compared to using a singular physical environmental or social dataset.[47] Highlighting populations that are especially susceptible to the effects of extreme heat is important to communities as they develop contingency plans for a changing climate. The conventional approach in environmental planning focuses on identifying the location where a hazard is likely to occur and concludes that persons in close proximity to the affected area are most “at-risk.” This method completely disregards any underlying social elements that influence the ability of people to respond and adapt to hazards.[48] Social vulnerability factors highlighted by epidemiologic studies should be accounted for. Our research found that individuals at higher risk of adverse health effects from extreme heat exposure include the elderly, urban poor, those living alone, and persons who work outdoors and do not have access to air conditioning.[49]

Poverty

Studies show that income levels across a city matches the spatial distribution of heat exposure.[50] Poverty and income-related variables have a relationship with the effects of heat in some studies.[51] [52] An increase in the risk of heat-related death was observed for persons earning less than $10,000 during the 1999 Chicago heat wave.[53] In Seoul, Korea, low-income individuals had higher mortality rates during hot weather.[54] An alternative dataset for poverty rate could include percentages of Non-Latinx, Black or African-American populations, the unemployment rate, and education levels. These social and economic indicators have been found to have close relations to poverty rates and they are demographic victims of the poverty cycle.[55] [56]

Community Health

Access to health services (i.e. differences between populations with private insurance coverage, no health coverage, or public health coverage) and disability were considered vulnerability factors for extreme heat episodes.[57] It has also been observed that preexisting health conditions may lead to susceptibility to heat-related illnesses and death.[58]

Age of Residents

Many epidemiological studies have shown the differences in heat mortality risk by age where the elderly and children tend to suffer greater health impacts from heat stress because of their limited ability to thermoregulate.[59] Elderly individuals, even in the absence of overt cardiovascular disease, are the most vulnerable population during prolonged environmental heat exposure, experiencing significantly worse health outcomes than any other age cohort. Individuals older than 65 years old, comprise most of the emergency room visits and deaths during heat waves.[60] Similar substitute datasets that can be used can be the average age of a dwelling unit, population above 65 years old, or even population with no health insurance and with an income below $65k.

<u>c. Feasibility of Implementing Cool Roadway Solutions</u>

In addition to obtaining and analyzing data for environmental and social parameters, it is imperative that the feasibility of implementation is also considered. This is a fairly broad category and includes anything that might influence the success of cool roadways in the city or area. For example, if a city is particularly prone to flooding, cities can consider reviewing the FEMA Flood Map to determine if it would be an effective city to host a pilot project. Alternatively, political willingness can be especially effective in speeding up the demonstrating siting process. For example, experts from San Antonio identified districts based on specific local knowledge and political direction that were keener to explore implementation, so that was a strong factor to consider.

To determine whether an area would be suitable for a pilot project of cool pavements, toolkit users should also know the current pavement characteristics and conditions. Alongside the other parameters aforementioned, these are practical considerations to identify if local conditions make the area suitable and convenient for the project. Screening toolkit users will need to collect additional information to assess the specific street transects in need of cool pavement project implementation, including: the total amount of pavement area (in miles), percentage of paved land area, ownership of different types of pavements, frequency of repair and maintenance, and materials used for current or surrounding road type.[61] This data will play a key role in tracking progress, identifying success, and highlighting areas of improvement for the project. It could also aid in raising awareness within the city if wider community involvement is in place for the maintenance of pavements.

3.5.3 Data Acquisition

In order to ensure that the index would be accurate and easy to assemble for city departments seeking to implement a demonstration site, the team looked mostly at publicly available data from government sources for computing both the social vulnerability and urban heat island severity. Below is a list of data sources for each of the measurements.

Source	Metrics
USGS Landsat 8 OLI *Collects imagery of the Earth's surface using sensors that can detect a total of 11 different bands of light.*	Land Surface Temperature Surface Reflectance NDVI
U.S. Census 2017 5-Year Survey *5-year survey last conducted in 2017.*	Poverty Rates Below 150% Levels Population > 65 Year Old Residents Without Health Insurance
Local Governments *Provided by members of the GCCA Cool Roadways Partnership.*	Air Quality (PM2.5) Road Conditions Traffic Patterns Political Willingness from District Leaders
FEMA *Contains information for disaster management.*	Flood Zones

Table 4: Data sources for index.

For data provided by the USGS Landsat 8, the team used the past 3 years of summer images from June, July, and August. Considering each city is located in the Northern Hemisphere, June, July, and August are the hottest months of the year. The team also filtered out any images that had greater than 10% cloud coverage. This approach yielded a sample of images to be able to accurately assess conditions. For U.S Census data, the team used the most up to date survey data in the analysis.

3.5.4 Data Processing

Using a combination of Microsoft Excel and QGIS, data from the above sources is cleaned, normalized between 0 and 1 for each parameter and then combined with weighted averages to produce an overall score. We conducted a correlation analysis to understand how each parameter influenced other parameters to determine where, if at all, double counting was occurring. Then, through a process of trial and error with two pilot cities (San Antonio and

Sacramento), the team determined suitable weights for each parameter. This methodology is outlined in Appendix D.

3.6 Cost Benefit Analysis

To better approximate the various benefits associated with cool pavements, a cost benefit analysis (CBA) was undertaken whereby the net social benefits of cool pavements are compared to traditional pavements. The various benefits associated with cool pavements include, but are not limited to, reduced surface and air temperature, improved air quality, improved community health, increased pavement durability, energy savings, carbon emissions reduction, vehicle gas savings from reduced air conditioning, and increased community comfort and productivity. The stated benefits are both important to city residents and city representatives. The analysis aims at assigning a monetary value to benefits for which there exists a market price or shadow price value to estimate the impact of cool pavements on society. This section will describe the methodology used to assign values to the various benefits while listing any underlying assumptions taken given that cool pavements are relatively new and require more research to obtain robust results.

1. Costs of Cooler Pavement Coating Material

Material costs vary depending on the chosen manufacturer. A study done by Bloomberg Associates on 13 different reflective coating products suggests that costs vary from \$1.7/m^2 (\$0.16/ft^2) to 37.75 \$/m^2 (\$3.51/ft^2).[62] Other costs mainly include equipment and labor which, according to a study done by Los Angeles, are estimated to be \$0.45/SF. It is important to note the following:

- The hard construction costs are 2014 estimates and are subject to change over time.
- Material costs are subject to change and might be lower in the future as the technology develops and becomes more widespread.
- The user will have the option to input the costs that they see fit to alter the CBA.

2. Energy Savings

Cool pavements increase a city's energy efficiency by reducing the need for extensive use of air conditioning in residential houses and by increasing the nighttime road visibility which reduces the number of streetlights needed.

According to a study conducted by the city of Chula Vista, reflective coatings on roofs and pavements, coupled with tree planting programs could reduce energy use by 10 to 40 percent.[63] To be able to estimate the energy reductions attributed to cooler pavements, the amount of energy used to heat or cool buildings and the ability of cooler pavements to reduce air temperatures have to be considered. Concerning the amount of energy used, a link is achieved between air temperature fluctuations and the amount of energy required to heat or cool a building. To get a reasonable estimate of this relationship, the heating degree days (HDDs) and cooling degree days (CDDs) have been used. HDD and CDD are a measure of how much heating or cooling is required based on a recorded temperature that is compared to a base of 65-degree Fahrenheit. By taking the average residential energy consumption and CDD over the winter and summer months, an estimate of the amount of energy required to cool a 1-degree Fahrenheit increase in air temperature is reached. The same methodology was adopted for the increase in natural gas consumption, by using the change in HDD, as a result of a 1-degree Fahrenheit reduction in air temperatures. Concerning the reduction in air temperature attributed to cooler pavements, given the lack of available data, a range of estimates in air temperature reductions has been taken to showcase the monetary benefit of energy savings attributed to different levels of air temperature reduction. It is important to note the following:

- The method of quantifying this is an estimate given the lack of granular data on residential building energy consumption.
- A nine-year period is taken since it is the maximum data available. Alternatively, a larger bandwidth of data is better to approximate more accurate results, especially since other factors, such as improved efficiency of home appliances, may contribute to lower energy use over the years.
- The energy rate in the U.S. is dependent on the state and thus the time of usage. During peak demand hours, the energy rate is typically higher. This is not reflected in the study which means that the results of energy saved from reduced cooling are an underestimate if customers are charged for peak demand.

- The increase in natural gas consumption at the building level for space heating is an overestimate since the study assumes that a decrease in outdoor air temperature of 1-degree Fahrenheit will cause a 1-degree Fahrenheit decrease in indoor air temperature, which is not the case given a building's insulation properties. This shows that the increase in natural gas consumption is an overestimate thus making the CBA more conservative.

According to a study done by the Heat Island Group at Berkeley Lab, reflective or light pavements increase the visibility for pedestrians and drivers at night. The increased glare makes it possible to use less street lighting which ultimately reduces the energy required to ensure a safe road visibility. The study shows how the same street would require 39 light fixtures if a dark pavement were adopted, compared to 27 light fixtures if a light pavement were adopted.[64] Taking their ratio would yield an estimate of the number of light fixtures needed on a dark paved road compared to a light paved road. This ratio is then coupled with the average energy use per streetlight to estimate annual savings. It is important to note the following:

- The adopted method is for estimation of reduced energy use for streetlights and should not be adopted as a technique to calculate the new number of streetlights needed after applying a reflective coating.
- Few studies have been conducted regarding this subject. Any future studies may yield more definitive results and should be replaced with the current estimation method.

3. Reduced Carbon Emissions

Given that cool pavements provide energy savings as mentioned in the previous section, reduced energy demand will mean less carbon emissions at the source. Considering the power mix and conversion factors of the utility provider in the study area, and the social cost of carbon, the total carbon savings are calculated.

4. Improved Air Quality and Community Health

Smog, whose principal component is ozone, forms more easily on the troposphere during hot days. This poses a major health issue, mainly towards communities with existing respiratory illnesses and the elderly who may be prone to higher risk exposure from heat. The EPA limit on the maximum average 8-hour ozone exposure helps determine the acceptable range of smog exposure. The ground level ozone standard, as set by the EPA, states that the maximum eight-hour average ozone concentration should not exceed 0.070 ppm (70 ppb).[65] To quantify the reduction of smog due to cool pavements, a study conducted by EPA suggests that smog level reductions range from 0.6 to 4.6 ppb per 1-degree Fahrenheit reduction of air temperature.[66] To better approximate this metric, the number of people, with respiratory illnesses, exposed to ozone levels above EPA's standard is determined. Here it is important to note:

- Given that there are inconclusive measurements on the reductions in air temperature associated with cool pavements, the monetary health benefit associated with cool pavements can only be showcased as a table showing the different monetized benefits as functions of different reductions in air temperatures.
- Although there is evidence that EPA's ozone standard is being exceeded in many areas, the extent to which information is available on the amount of exceedance depends on the city and its efforts at measuring this. For this reason, the monetary health benefit will be a function of assumed ozone level exceedance. If a city has data on this, then it can simply input their data and get more accurate results.
- The estimation assumes that all lives that are at risk will be saved. It also does not consider partial lives saved from reduction in ozone levels that do not result in ozone levels below the EPA standard. The way the monetization is done is to showcase the large health benefit associated with cooler pavements.

Ozone Concentration (ppm) (8-hour average, unless noted)	Air Quality Index Values	Air Quality Descriptor
0.0 to 0.064	0 to 50	Good
0.065 to 0.084	51 to 100	Moderate
0.085 to 0.104	101 to 150	Unhealthy for Sensitive Groups
0.105 to 0.124	151 to 200	Unhealthy
0.125 (8-hr.) to 0.404 (1-hr.)	201 to 300	Very Unhealthy

Figure 3. Average 8-hour exposure index.[67]

5. Increased Pavement Durability

Pavements are subject to deterioration with time. Part of their weathering is due to the asphalt binder heating up, making the pavement loose and at risk of deterioration.[68] According to a study referenced by Los Angeles' cost benefit analysis, reducing the temperature of asphalt by 10 degrees Celsius yields more than ten times increase in the pavement lifetime. A 0.1 increase in pavement albedo reduces pavement peak temperatures by about 6.5 degrees Fahrenheit (3.6 degrees Celsius).[69] This suggests the potential benefits in terms of pavement longevity to be significant. Given the lack of research on how much cooler pavements actually increase the longevity of a pavement, the CBA assumes the increase to be directly correlated with the lifetime of the cooler pavement coating material. A study done by Bloomberg Associates suggests their lifetime to vary by manufacturer.[70] For conservative reasons, their lifetime is taken to range from 5 to 7 years. Removing the reduced annual maintenance costs of the roads over the lifetime of the cooler pavement coating material can yield an estimate for the potential benefits.

4. Case Study: San Antonio

To demonstrate the use of the toolkit the team developed for the GCCA, the following section outlines how a city would engage with it to develop a cool pavements project. The team designed the workflow and material based on discussions and interviews with industry experts discussed in section 3.1-3.4 of this report.

4.1 Screening Process

Using the process outlined in section 4.2 - 4.4, the team produced a choropleth map to visualize the highest priority areas within a city. In discussions with city officials from San Antonio, the team also learned which council districts are most likely to be willing to implement a cool pavements demonstration site. Thus, the team included this information as a feasibility indicator in the score and removed areas from the screening process outside. The team also produced a tabulation of the top results so users can understand exactly why these areas are rated as such.

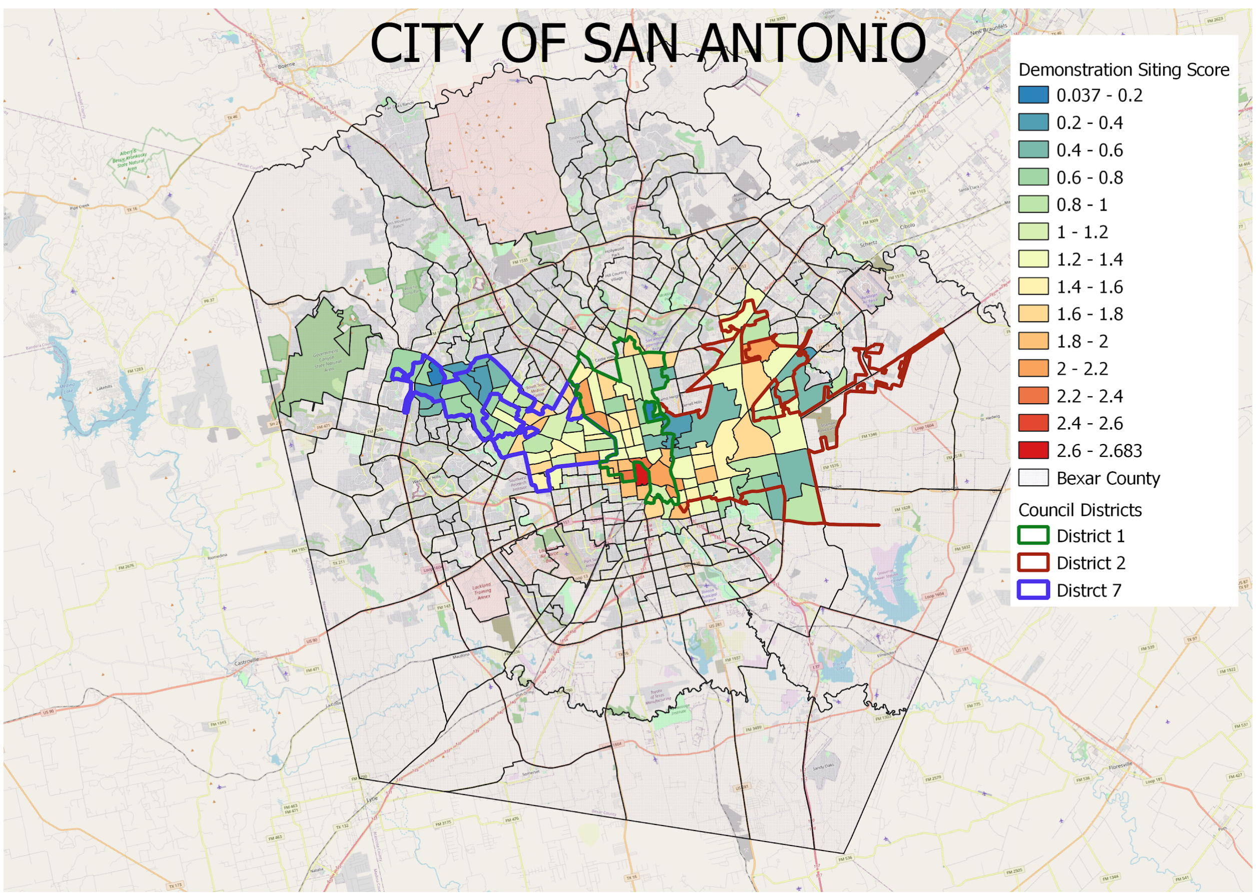

Figure 4: Choropleth map for San Antonio, TX.

Figure 4 above shows that there are several priority areas (in red) that, according to the index, would benefit most from cool pavement based on UHI mitigation strategy. Diving deeper into the underlying data, the team surfaced the few census tracts and their associated data on the metrics on which they were scored:

Census Tract	Combined Score	Temp Score	NDVI Score	Uninsured Score	Age > 65 Score	Poverty Score
48029110600	2.683	0.761	0.171	0.538	0.783	0.773
48029110700	2.384	0.734	0.112	0.608	0.637	0.517
48029170102	2.238	0.525	0.54	1	0.419	0.834
48029110100	2.112	0.712	0	0.464	0.393	0.543
48029180201	2.069	0.756	0.506	0.509	0.572	0.738

Table 5: San Antonio Placeholder Top 5 Census Tracts

The next step for the city official would be to conduct site visits to these five areas, shown in Table 5, in order to verify the data as well as identify specific sites for pavement coatings. City officials should look for school parking lots, shopping areas, heavily trafficked sidewalks within these districts to further refine their demonstration siting search.

4.2 Defining Cool Pavement Projects

Determining which type of cool pavement material to use is heavily reliant on the type and condition of the pavement. This makes it necessary for the user to conduct site visits to the areas outputted by the tool to determine which cool pavement to opt for. Further, the user should determine the scope of the project being studied. This is necessary since it helps in determining the initial cost of installing cooler pavements, which is charged on a per square foot basis. Another important factor is the number of streetlights that are currently on the road. The user would require this information to be able to have an idea of the reduced energy consumption as a result of increased nighttime visibility.

For the reasons mentioned above, the cost benefit analysis conducted on San Antonio does not include the initial cost of the pavement, the benefits of reduced nighttime streetlights or the increased pavement durability.

4.3 Cost Benefit Analysis

As stated previously, there are many benefits associated with cooler pavements. To better showcase this benefit, three metrics have been monetized: the energy savings due to lesser cooling needs in homes, the social cost of carbon due to lower energy consumption, and the impact of reduced tropospheric ozone on the communities at risk.

Energy savings have been calculated using CDDs and HDDs and residential energy consumption patterns over the past three years for both summer and winter months. After determining the estimated reductions in energy use based on air temperature reductions, the social cost of carbon was taken along with the power mix of San Antonio to determine the net benefit in terms of carbon reduction as showcased in table 6.

Air Temperature reductions from cooler pavements (Degree F)	Estimated Reductions in energy bill (mill $/year)	Estimated increase in natural gas bill (mill $/year)	Net Benefit (mill $/year)	Cost of Carbon removed (mill $/year)	Net Benefit Including Social Cost of Carbon (mill $/year)
1	24	8	16	1.7	18
2	48	16	32	3.4	35
3	73	24	49	5.1	54
4	97	32	65	6.8	72
5	122	40	82	8.5	91
6	146	48	98	10.2	108

Table 6: Net Benefit of Energy & Carbon Reduction from Cooler Pavements, San Antonio Texas

San Antonio experiences high levels of smog during the summer months. In fact, the most recent measurements of tropospheric ozone in San Antonio show that the area is around 15 parts per billion (ppb) above the EPA's 70 ppb standard.[71] It was determined that San Antonio has approximately 1,050 people at risk of dying due to these increased ozone levels. By taking the value of a statistical life into consideration, a net benefit of around $10 billion is estimated for a reduction in air temperature of around 6 degrees Fahrenheit.

5. Conclusion

As the world continues to urbanize and temperatures continue to rise, the UHI effect is going to become more pronounced and dangerous. Thus, there is growing interest in urban cooling solutions, such as cool pavements, cool roofs and green infrastructure. The team was specifically enlisted to help with the promotion of cool pavements and tasked to develop a screening toolkit that would help city governments identify areas most suitable for the implementation of cool pavement solutions. One of the team's main priorities was to address the environmental injustice of disadvantaged and marginalized populations disproportionately affected by extreme heat. Thus, the team developed screening criteria for city governments that would account for environmental, social and political factors. It was a challenge to strike a balance among the chosen parameters needed to accurately capture the nuances of environmental planning while also ensuring the data was accessible and user-friendly. The screening toolkit was developed to simplify the process of implementing cool pavement solutions and aims to inspire more intra-government cooperation as planning officials begin to work more closely with local data experts.

By purposefully emphasizing social determinants of heat vulnerability, the toolkit encourages city governments to take a holistic approach towards environmental planning more broadly. The maps and analysis that the toolkit produces depict vulnerable hotspots and should help government officials build a convincing case to gain the resources necessary to implement a pilot project. Additionally, the feedback collected from participating cities can be integrated seamlessly into the index, allowing for continuous improvement. Despite the project's focus on cool roadways, the team believes that cool pavement solutions should be used as part of a comprehensive strategy to mitigate UHI effects. The team hopes that this project will further the conversation on how to effectively use data and technology to address environmental injustices and mitigate the impact of future climate hazards.

6. Appendix

Appendix A: List of Questions for Manufacturers

1. How is the [insert product name] integrated into the asphalt road? i.e. is it a coating material laid on top of existing asphalt pavements, or is it a new asphalt mix that replaces old pavements?
2. Are there any worries concerning the added upfront costs?
3. How have city constituents (city representatives, community) reacted to the [insert product name]?
4. Were there any barriers in terms of government regulations, health effects and community resistance? Are there any other barriers or opportunities that you would like to speak about?
5. Have you previously considered the effects of the [insert product name] on the urban heat island effect? If you have, please expand on the topic.
6. What are the most important considerations when evaluating pavement products? (i.e. heat mitigation effectiveness, maintenance cost, upfront cost, community resistance, government regulations, other…)
7. What factors do you consider before laying down the [insert product name]?
    a. Surface Temperature
    b. Air Quality
    c. Heat Vulnerability
    d. Air Temperature sensing (at 2m height)
    e. Critical Infrastructure
    f. Community Health
    g. Pavement information (i.e. age, thickness, traffic volume)
8. What city officials have you worked with when implementing [insert product name]? If there were any barriers, how did you overcome them?
9. Do you have any statistics on the increased longevity of pavements from [insert product name]? Does this relate to coating materials used by cooler pavement manufacturers?

Appendix B: Survey for RFI Cities

1. What are your primary concerns regarding urban heat island and its local effects?

Select all that apply:

☐ UHI mitigation for air quality improvements

☐ UHI mitigation for reduction in surface temperature

☐ UHI mitigation for improvements in equity issues

☐ UHI mitigation for health issues

☐ UHI mitigation for energy savings

☐ UHI mitigation for climate response

☐ Other

2. What are the reasons you are interested in cool pavements?

Select all that apply:

☐ UHI mitigation for air quality improvements

☐ UHI mitigation for reduction in surface temperature

☐ UHI mitigation for improvements in equity issues

☐ UHI mitigation for health issues

☐ UHI mitigation for energy savings

☐ UHI mitigation for climate response

☐ Other

3. What are the most important considerations when evaluating cool pavement products? (ie. heat mitigation effectiveness, maintenance cost, upfront cost, etc..)

Long answer text:

4. What concerns do you have about cool pavements as you understand it today?

Select all that apply:

☐ Costs

☐ Government Regulations

☐ Local Manufacturers

☐ Safety Concern

☐ Community Resistance

☐ Other

5. If you selected any concerns, please elaborate on your answer.
Long answer text:

6. Are there particular neighborhoods, locations, or streets that you are already considering for a pilot? If so, why?
Long answer text:

7. Has your city done any studies or monitoring of the following.
Select all that apply:

☐ Surface Temperature

☐ Air Quality

☐ Heat Vulnerability

☐ Air Temperature Sensing

☐ Other

Specify other:

8. Is the urban heat island effect and its impacts common knowledge amongst city residents and have they demonstrated concern?
Long answer text:

9. Is the urban heat island effect and its impacts common knowledge amongst local government colleagues (in particular public works officials) and have they demonstrated concern?
Long answer text:

10. What stakeholders within the community or local government would be involved with the cool pavements pilot project (ie. roads department, sustainability officers, community leaders, etc.)?
Long answer text:

11. Has your city previously taken any of the following measures to reduce the urban heat island effect or included heat mitigation in strategic plans, goals, or other such documents? Select all that apply:

☐ Trees and Vegetation

☐ Green Roofs

☐ Cool Roofs

☐ Cool Pavements

☐ Smart Growth

☐ Other

If you checked boxes in Q11, could you briefly describe the nature of the policy? (e.g., strategic goal/target, awareness-raising campaign, incentive, mandate/regulation, leading by example with city assets and services).
Long answer text:

12. Is there anything else you would like to add?
Long answer text:

Appendix C: List of Questions for City Representatives

1. What are your primary concerns about the Urban Heat Island effect?
2. Have you previously enacted any UHI mitigation strategies? If yes, why?
3. What are the most important considerations when evaluating cool pavement products? (i.e. heat mitigation effectiveness, maintenance cost, upfront cost, community resistance, government regulations)
4. Have you previously been in contact with a cool pavements manufacturer?
5. Are there particular neighborhoods, locations, or streets that you are already considering for a pilot? If so, why?
6. Has your city done any studies or monitoring of the following, and is it publicly available data?
    a. Surface Temperature
    b. Air Quality
    c. Heat Vulnerability
    d. Air Temperature sensing (at 2m height)
    e. Critical Infrastructure
    f. Community Health
    g. Pavement information (i.e. age, thickness, traffic volume)
7. Have city residents expressed any concerns about the UHI effect?
8. Have any city officials expressed any concerns about UHI? If so, are any actions being taken in terms of policy requirements or budget allocations? (This may include any strategic goal/target, awareness-raising campaign, incentive, mandate/regulation, leading by example with city assets and services)
9. Relating to the previous question, if you answered yes, who would be the city officials involved in advancing cooler pavements pilot projects?

Appendix D: Demonstration Siting Index Formulation

Urban Heat Island Parameters

Land Surface Temperature

The team used the QGIS RS&GIS plugin to compute the land surface temperature, which follows the USGS formulation of Land Surface Temperature (LST).[72] The images provided by Landsat provide a 30m^2 resolution of Earth's surface, which is significantly smaller than the area of a census tract. The team downloaded data from 2017 - 2020 for the months of June, July and August. The summer months were used because that is when the urban heat island (UHI) effect is greatest in the Northern Hemisphere. The team then averaged the LST values for each image and performed zonal analysis to average the land surface temperature measurements on a 30m^2 resolution for each census tract.

Normalized Difference Vegetation Index

The normalized difference vegetation index (NDVI) provides a measurement of greenness. This measurement is often computed from satellite imagery to assess forest health or agriculture field health. For urban settings, areas with greener canopy and less concrete or dirt exposed will have a higher average NDVI. The prevalence of vegetation reduces the UHI effect through evaporative cooling and shading. To compute this measurement, the team used the near infrared (band 5) and red (band 4) images from Landsat 8, which provide a 30m^2 resolution. The following equation computes the NDVI for a given region.

$$NDVI = \frac{NIR - R}{NIR + R}$$

Much like with the LST, the data from 2017 - 2020 during June, July, and August was used. Again, the team averaged each of the NDVI raster images and then took the average again for each census tract zone.

Air Quality

Air quality measurements are derived from air quality sensors placed throughout a city. While there are some national databases of air quality sensor data, they are not granular enough to differentiate the air quality in different areas of the city. Thus, the team relied upon air quality data provided by cities when available. Where cities did not have this data available, the team omitted the information from the index. The standard measurement to use for air quality is particulate matter 2.5, which measures the concentration of particulate matter in the air greater than 2.5 microns large and tropospheric ozone. Other size particulate readings can be used as well so long as they are consistent throughout the city. For this study, the parameter considered was mainly ozone, given that it is the primary constituent of smog.

Social Vulnerability Parameters

All social vulnerability parameters are derived from the U.S. Census. To understand differences within a city, the team used the census' most granular geographic space characterized by census tracts.

Poverty

To assess the relative poverty of different areas within a city, the team looked at the percentage of the population that falls below the 150 percent poverty threshold. In doing so, this provides a sense of the relative wealth of a certain area compared to others.[73]

Community Health

To assess the vulnerability of the community to health concerns, the team analyzed the percentage of residents earning less than $65,000 in income per year without health insurance as being uninsured is a contributing factor to social vulnerability.[74]

Age of Resident

Older populations are more vulnerable to heat-related mortality, thus understanding the age of the population is critical to understanding heat vulnerability.[75] The team used the percent of the population over the age of 65 to quantify this parameter.

Feasibility

FEMA Flood Zone AE

Cool pavement coating can be damaged during severe floods, so the team looked to FEMA maps to exclude areas that are prone to flooding. Zone AE has an annual likelihood of flooding equal to or greater than 1%.

The process of index formulation yields weightings for each of the previously listed parameters. The first step to this process was normalizing each of the parameters to a value between zero and one for the weights to have equal weights themselves. To normalize the values, the team used the following formula to simply scale the value between the maximum and minimum value in the dataset:

$$NV = \frac{Value - Min(values)}{Max(values) - Min(Values)}$$

Where NV is the normalized value. Once each parameter is normalized, the team conducted a correlation analysis to see how closely correlated each parameter is to one another.

Correlation Matrix (1 Being Highly Correlated, -1 Being Inversly Correlated)					
	NDVI	Temperature	Poverty	Uninsured	Age > 65
NDVI	1.00000				
Temperature	-0.67096	1.00000			
Poverty	0.10837	-0.05911	1.00000		
Uninsured	-0.16489	0.19342	0.00851	1.00000	
Age > 65	-0.03376	-0.02221	0.15200	0.23404	1.00000

Table 7. Correlation Analysis for San Antonio, TX

Based on the above analysis and consistent with expectations, NDVI is negatively correlated with temperature. This makes sense considering vegetation coverage reduces land surface temperature. Thus, the team weighed NDVI negatively in the overall assessment as high NDVI areas do not have the greatest need for cool roadways solutions. Aside from temperature and NDVI, all other variables either have weak or no correlation, which gives a strong indication that the team did not double count by including both measurements in the index.

To formulate the index, the team selected two cities with different climates in order to experiment with two sets of data from varying conditions. By creating a tool to assess how different weights on each parameter impact the overall distribution of scores across each census tract, the team was able to study how changing the weights impacts the variance of score results.

For the base case, the team used equal weights on each criteria except NDVI, which has an equal but negative weight due to the inverse correlation. The result yielded a histogram with a fairly normal distribution:

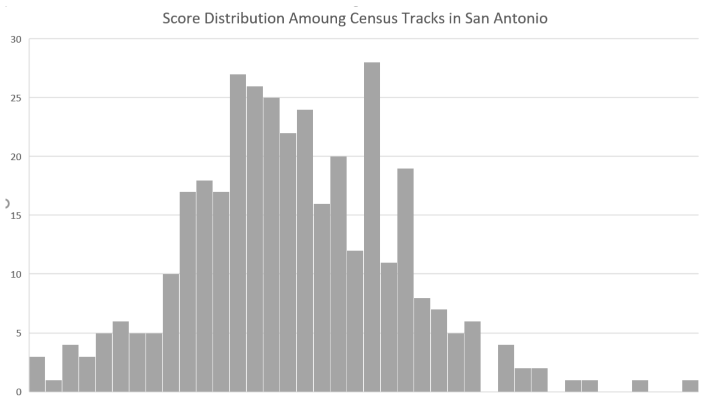

Figure 5. Source distribution among census tracts in San Antonio, TX.

As depicted in the figure above, there are just a few outliers with high scores compared to the rest of the census tracts. It is important to investigate these neighborhoods manually to confirm that they would indeed be good candidates for UHI mitigation strategies through cool pavements. The map below shows the top five census tracks based on this equal weighting scheme for San Antonio, Texas.

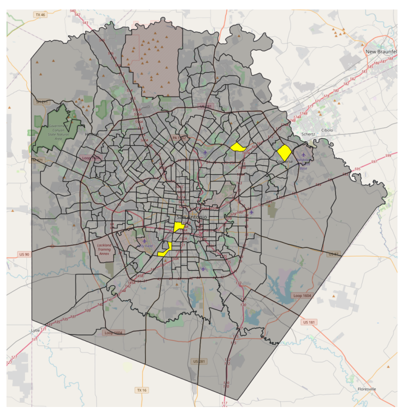

Figure 6. Top four census tracks based on equal weights for San Antonio, TX.

The team then looked more closely at the underlying data for each of these outliers to verify that they would indeed be qualified candidates. The fourth most highly ranked area is one near the Port of San Antonio. Interestingly, about half of the area is industrial while the other half is residential. The industrial nature of this region makes it the second most qualified out of all the regions, which skews the ranking. Otherwise, this area has a below average uninsurance rate and average poverty and age ranking. Thus, to further improve the accuracy of the index, the team reduced the weighting on temperature and NDVI so that they contribute less to the overall score. After adjusting the weights, the new ranking kept 3 of the 4 tracts the same while removing this semi-industrial area.

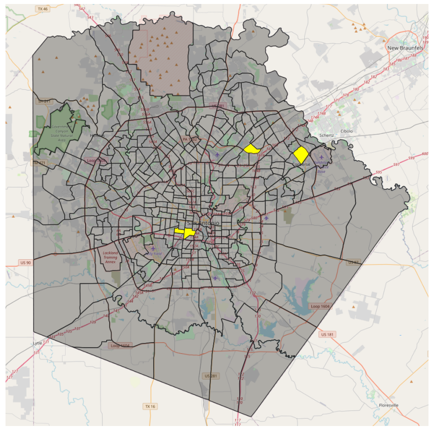

Figure 7. Top four census tracks based on revised weighting in San Antonio, TX.

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The team would also like to thank all of the city representatives we contacted over the course of the semester, especially those that used our tool and provided valuable insight.

8. Acronyms

In alphabetical order:
ARD: Ready Data Package
CBA: Cost Benefit Analysis
CDD: Cooling Degree Day
GCCA: Global Cool Cities Alliance
HDD: Heating Degree Day
NDVI: Normalized Difference Vegetation Index
PED: Primary Energy Demand
PMI: Petrochem Materials Innovation
REAS: Rubberized Emulsion Aggregate Slurry
RFI: Request for Interest
UHI: Urban Heat Island

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