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THE UNIVERSITY OF ARIZONA®

Assessing Cool Corridor Heat Resilience Strategies for Human-Scale Transportation

Final Report

NITC-RR-1483

by

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16. Abstract

Road pavement is a known contributor to the urban heat island effect. Several vendors are providing engineered pavements coatings—known as “cool pavement”—to reflect light and, therefore, reflect heat to reduce the thermal load of roads. Few of these cool pavements have been evaluated outside lab conditions, where they tend to rely heavily on surface temperature measurements with the assumption that lower surface temperatures result in lower ambient air temperatures in real-world practice. Further, while heat is detrimental to the pedestrian and cyclist experience and health, almost no research exists documenting the experience of the cool pavement on active travelers, including their perception of heat. The City of Tucson conducted a pilot application of the PlusTi asphalt rejuvenator, a cool pavement product, in 2021 as a part of its Parks and Connections Bond work. We conducted a before-after, case-control quasi-experimental design to evaluate the impacts of the cool pavement product on heat metrics, including surface temperatures (TS) of the pavement, ambient air temperatures (TA) of the area, and thermal comfort as measured by wet bulb globe temperature (WBGT). The study design did not allow us to test for before-and-after treatment differences in TS, as other factors likely contributed to observed differences. Once autocorrelation is accounted for, we estimated the PlusTi pavement rejuvenator resulted in 0.3°F less TA observed and no statistical difference measured in WBGT.

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DISCLAIMER

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1.0 EXECUTIVE SUMMARY

Transportation infrastructure, such as roads and parking lots, is a known contributor to the urban heat island (UHI) effect. The radiant and waste heat from vehicles compounds the contribution of transportation infrastructure to the UHI effect. While heat is detrimental to the pedestrian and cyclist experience and health, little research exists documenting the experience of heat for active travelers, including their perception of and personal exposure to heat. Despite this gap in evidence, professional interest is growing in creating “cool corridors” to mitigate the UHI effect and support the movement of non-vehicular travelers within communities. Common heat mitigation strategies along transportation infrastructure include green stormwater infrastructure and tree canopy for shade. Several vendors are providing “cool pavement coatings” to reflect albedo and reduce the thermal load of roads. However, few of these cool pavement coatings have been tested in real-world conditions, including tested with other cool corridor strategies.

The City of Tucson is part of a Global Cool Cities Alliance Cool Roadways Partnership and piloted an application of the PlusTi asphalt rejuvenator, a cool pavement product, in the winter of 2021 as a part of its Parks and Connections Bond work. **We conducted a before-after, case-control quasi-experimental design to evaluate the impacts of the cool pavement product on heat metrics**, including surface temperatures (TS) of the pavement, ambient air temperatures (TA) of the area, and thermal comfort as measured by wet bulb globe temperature (WBGT).

While many companies advertising cool pavement treatments focus on TS measurements, both ambient and WBGT better reflect the perceived heat human experience of heat at a pedestrian level. We then regressed TA and WBGT upon the time of day, presence of shade, wind speed, airport ambient temperature, and site location to compare the difference between before-and-after cool pavement treatment installation**. The study design did not allow us to test for before-and-after treatment differences in TS, as other factors likely contributed to observed differences. Once autocorrelation is accounted for, we estimated the PlusTi asphalt rejuvenator resulted in 0.3°F less TA observed, and no statistical difference measured in WBGT.** Controlling for influential environmental factors, this degree of decrease in TA may be considered negligible, or at least very challenging to observe as a pedestrian. Although we did not capture a decrease in measured thermal comfort at a human scale, we still see this as a positive outcome. Our framework for measuring human-scale thermal comfort allowed us to determine whether the reflective nature of the treatment may be increasing heat experienced by pedestrians—or, in this case, not.

In addition to providing an evaluation of the City of Tucson’s cool pavement pilot project, our results can help guide the City of Tucson and other municipalities in selecting future cool corridor heat resilience strategies. The results contribute to understanding how the changing climate may impact human-scale transportation, including modal shifts and physical activity-based public health outcomes.

2.0 INTRODUCTION

Heat is the number one weather-related killer in the United States , estimated to cause at least 12,000 heat-related and -caused deaths each year (Shindell et al., 2020). As communities around the world are experiencing more frequent and hotter extreme heat events due to climate change (Hayhoe et al., 2018), the need for cooling our built environments is both substantial and immediate. Cool pavement products, such as coatings and rejuvenators that behave like sunscreen for our pavements, are being developed and deployed to improve the heat resilience of our infrastructure, but we continue to have a limited understanding of how these treatments impact the experiences of our most vulnerable travelers: pedestrians, cyclists, and transit riders.

The methods that researchers and practitioners currently have for evaluating new cool pavement treatments and technologies are still in their infancy. While simulations and lab tests of cool pavement outcomes are useful, there is a growing need for curating protocols around natural experiments to better understand human thermal comfort across time and space. In this study, we evaluate the application of a cool pavement treatment, the PlusTi asphalt rejuvenator, in Tucson, AZ, as part of a pilot test to understand the costs and benefits of such treatments. Many cool pavement treatments emphasize the ability to extend the lifespan of infrastructure, especially in areas that experience chronic heat events—like the long and hot summers of Arizona. In our work, we emphasize measurements that approximate human thermal comfort. To this aim, we have three objectives:

- Objective 1: Create a multidisciplinary conceptualization of transportation systems focused on their contributions to the urban heat island (UHI) effect, travelers' personal heat exposure, and consequential heat health from a multimodal perspective.
- Objective 2: Articulate and test the spatial distribution and decay of heat along roads at a pedestrian- and/or cyclist-scale with and without climate resilience strategies for cool corridors such as lane width; cool pavement coatings; and trees or green stormwater infrastructure in place.
- Objective 3: Increase the capacity of the research team and field by automating data cleaning and cursory analysis of personal heat exposure measures using off-the-shelf instrumentation and open-source software.

The primary purpose of the study includes developing this interdisciplinary area around transportation planning, public health, and climate adaptation (objective one). We then develop and refine our natural experiment protocols to accommodate the lessons learned around the complexity of the kind of natural experiments needed to better understand human-scale impacts of cool corridor treatments (objective two). As part of this process, we share our protocols and the scripts developed to analyze human comfort so that others may build on our work (objective three). While our study focuses on the evaluation of cool pavement products on human-scale heat experiences, this work may also be relevant for those interested in the measurement of heat in practice, including disciplines such as civil engineering; urban planning; landscape architecture;

urban design; occupational safety; retail and/or building management; and transit or active travel planning and advocacy.

There are four direct outcomes of this study. First, we developed a conceptualization of personal heat exposure associated with multimodal transportation — especially for active travelers — by better articulating how the transportation system intersects with climate change and heat. Second, our work helped support the City of Tucson by evaluating cool pavement pilot(s) and considering these questions. Third, we increased knowledge on the design of cool corridor transportation infrastructure to reduce heat risk for pedestrians, cyclists, and transit users and supported local-level decisions through a decision-making framework. And fourth, we refined methodologies and analyses (i.e., R code scripts, protocol documentation) to encourage better integration of personal heat exposure risk in the transportation planning field and other applications, such as citizen science initiatives with UArizona's Extension office.

This report is organized as follows. We first provide an overview of the context of the heat as an increasing climate risk. Our literature review is provided as a working paper in the appendix, so instead, we introduce our heat research agenda, the Tucson context, and an overview of cool pavement treatment products, including a description of the one evaluated in this study. We then describe our study design, starting with our development of a two-pronged study (natural experiment including before-after and case-control) of different types of heat measurement, and a description of the methods we used to evaluate this natural experiment. Next, we describe and interpret our results, and we conclude with a summary of our findings and lessons for practice.

3.0 BACKGROUND

Climate change is resulting in the increased frequency and intensity of extreme heat events, and increasing chronic heat as average temperatures rise (Hayhoe et al., 2018). Both extreme heat events and chronic heat impact health, human thermal comfort and, ultimately, safety during travel. Further, increases in heat are often most concentrated in the urban environment, resulting in an urban island heat (UHI) effect. Due to climate change, the UHI effect and historically racist land use practices such as redlining and disinvestment, heat disproportionally impacts minority, low-income, and marginalized communities (Hoffman et al., 2020; Wilson, 2020).

Urban planning—with its influence over the built environment—has a direct role in how the UHI effect impacts human behavior and health. Urban planners are critical in understanding, orchestrating, and implementing greenhouse gas (GHG) and heat mitigation measures. Transportation planning, in particular, has played a large role in contributing to climate change and the UHI effect. Through concentrated efforts on creating car-focused transportation plans and efforts, transportation planners have contributed heavily to the associated GHG, impervious surfaces, and heat islands in the urban environment.

Fortunately, transportation planners are also in a position to increase “heat resilience” by proactively mitigating and managing heat across the systems and sectors it impacts (Keith & Meerow, 2022). This includes reducing their communities’ contribution to climate change and the UHI effect by supporting lower-GHG transportation modes such as active travel and transit. Transportation planners can also implement heat mitigation strategies along streets: cool pavements, urban greening, street and building morphology, and leveraging water for evaporative cooling (see literature working paper, Appendix A). These heat mitigation strategies help support thermally comfortable environments that promote multimodal streets and reduce the overall UHI effect. This reduces GHG and promotes healthy, safe, and active communities.

3.1 HEAT RESEARCH AGENDA

The authors drafted a letter to the U.S. Department of Transportation (USDOT) in response to their strategic framework goals in January 2022. In this section, we share a version of the letter with limited revisions to broaden the context of our feedback.

Extreme heat falls under multiple draft goals in the overall USDOT strategic framework, including Climate & Sustainability; Safety; and Equity. Despite the strong relationship between extreme heat and draft goals, heat is often missing from the context of transportation resilience. For instance, while the impact of flooding is frequently considered in transportation resilience, extreme heat is the number one weather-related killer in the U.S. (Shindell et al., 2020). Heat is a complex hazard that comes in many forms. Most people associate extreme heat with distinct heat waves, such as the historic heat dome in the summer of 2021 that resulted in over 1,200 deaths in the Pacific Northwest and Western Canada (British Columbia, 2021; Popovich & Choi-Schagrin, 2021). However, extreme heat is also a chronic hazard in many regions. For example, the extreme heat in the arid and semi-arid Southwest or the humid Southeast is equally challenging to manage from a transportation and public health perspective. We intuitively understand heat, seeking shade when the sun is beating down. Yet due to the context-specific nature of weather, built environments, community supports, and individualized resources, measurement can be difficult and individualized risks vary widely. For these reasons, heat research and practice has lagged behind the increasing threat of heat in many sectors, including transportation.

Extreme heat will continue to intensify across the globe due to climate change and the UHI effect, both of which have a major connection to built transportation infrastructure and transportation-related GHG emissions. Historically hot communities will become hotter, and historically cooler communities will continue to break new temperature records. Unsurprisingly, communities most vulnerable to heat due to their built environments are also often communities—black, brown, and low-income—with the least resources. In this context, it is critical that USDOT, through the National Institute for Transportation and Communities (NITC) and other University Transportation Centers (UTCs), elevate extreme heat-related research and evaluation for all transportation modes.

The PI of this project, Dr. Keith, recently authored a Nature commentary on the need for heat governance (Keith et al., 2021). Applying the six principles for advancing heat governance from this commentary to multimodal transportation research themes suggests that the following areas should be elevated over the next five years:

Mitigate heat: In addition to transportation-related GHG emissions, the transportation sector relies on physical infrastructure that serves as a major contributor to the UHI effect; this will increasingly require mitigation. The Healthy Streets Program of the 2021 Bipartisan Infrastructure Bill funds the two most promising strategies: tree shade and cool pavements. Shade—especially from vegetation such as trees—has firm empirical study behind it. Yet cool pavements are largely unevaluated in the field. This is a primary objective of this project, and we recognize others are doing much-needed complementary work.

In general, practitioners need to understand the compatibility of various heat mitigation strategies even as cities rush to do everything they can to reduce the overall UHI. We also need to carefully consider the multimodal impacts of new technologies. Ideally, heat mitigation measures should complement other public health goals, such as increasing physical activity in a safe way. For example, returning to cool pavements, we need to understand which pavements reduce both surface and air temperatures while also being sure the reflection does not increase risk of collisions through glare or skin cancer risks of pedestrians or transit users from increased ultraviolet (UV) exposure.

Manage heat risks: The transportation system serves a vital social and economic role in connecting people to places and goods regardless of temperature. To date, most transportation research has focused on managing the risks of heat on large infrastructure such as bridges, asphalt performance, or airline travel. However, unmanaged, extreme heat can directly result in the loss of human life. It can also be highly disruptive to everyday human life. For example, extreme heat events stress transportation systems as emergency health transports are needed, and those without air-conditioning use some sort of transportation to get to cooling centers. During chronic heat, we need to understand how to better support ongoing healthy behaviors through ideas such as "cool corridors" for non-vehicular travelers and educational campaigns about when it is no longer safe to be outdoors for active travel.

Develop transportation and heat metrics: Heat exposure and risk are context-specific. We need flexible, evidence-based heat metrics that span the transportation sector, modes, and contexts. Metrics should anticipate our multimodal, lower-GHG future and address both short-run extreme heat events and longer-term chronic heat exposure. In addition, we should be tracking investment levels for heat-mitigating infrastructure. Joint metrics with our public health partners are also needed.

There are also some exciting opportunities for the transportation sector. Extreme heat measurement, modeling, and monitoring are quickly coming down in scale from regional satellite imagery measures—the domain of meteorologists and climatologists—to street-level measures that better align with travelers' thermal comfort or personal heat exposure experience. Transportation modelers—with expertise in air quality spatial modeling highly dependent on localized meteorology—have a potential role in developing the measures and modeling methodology of human-level heat exposure. As sensors come down in size and price, street-level heat surveillance systems in an era of big data and the internet of things could be vital in monitoring and understanding the spatial distribution of heat and managing high-heat situations.

Coordinate initiatives and build heat institutions: Heat governance is challenging because everyone is impacted, but no single department is an obvious owner of the challenge. In the transportation sector alone, metropolitan planning organizations might have regional heat modeling capacity, while state and local DOTs have control over the type/treatments of pavement, even as other city departments control the planting and maintenance of street trees. Even a simple question in our own city of Tucson of increasing shade at transit stops resulted in no less than six city departments simultaneously expressing interest and concerns. Thus, research into how transportation and planning departments are considering and managing their heat mitigation and adaptation portfolio is desperately needed to elevate initiatives and relationships that are working.

There is a need for better coordination of heat research and implementation at the state and national levels. U.S. NOAA, EPA, and DOT all have a vested interest in research around green infrastructure along transportation facilities; the CDC and NIH should be tracking the direct and indirect impacts of these efforts on human health and healthy behaviors. It may be time for a heat-specific research grant mechanism co-sponsored by multiple agencies. For example, U.S. DOT's participation and support of the U.S. National Integrated Heat Health Information System (NIHHIS) would provide a valuable interdisciplinary effort. There would be a substantial benefit if at least one of the 2021 Bipartisan Infrastructure Bill regional Centers of Excellence for Resilience and Adaptation would focus on heat research.

Advance heat equity: Finally, heat varies spatially. Neighborhoods with a high proportion of minority or low-income households are more likely to live in an area 5-10°F degrees hotter than those in wealthier neighborhoods. Much of this is linked to greenspace (or lack thereof) and impervious and heat-capturing surfaces of our built environment—legacies of urban and transportation planning. The same people who live in these warmer neighborhoods also have less ability to mitigate their heat risk. For example, low-income individuals are more likely to live in a home without air conditioning and, thus, need to seek respite from the heat at a cooling center. They are also more likely to have underlying health conditions that are exacerbated by heat risk. Specific to transportation, these individuals are less likely to own a vehicle and, thus, are more reliant on walking, biking, and transit trips for basic needs. As such, the transportation sector has an obligation to prioritize heat research that advances equity spatially and targets the populations most at risk. The explicit focus on heat equity will also help fulfill the U.S. DOT's Justice40 goals.

In sum, transportation planners need to mitigate and manage heat in the context of increasing climate change impacts.

3.2 THE STUDY CONTEXT

Tucson has an estimated population of 543,242 and a metropolitan population of just over 1 million residents as of 2021 (U.S. Census Bureau, 2022). Tucson is in the Sonoran Desert and has a semi-arid climate, characterized by low humidity, cool winters, and hot summers which include a dry season in June and the monsoon between June 15 and September 30. Tucson's precipitation is variable from year to year, but most occurs during the monsoon and winter. Over the last 30 years, the number of storms during the monsoon has decreased, while the average amount of precipitation has not, meaning there have been less frequent but more intense storms in the region (Meadow et al., 2019).

Tucson has a long-term annual average temperature of 66.8°F; however, almost every year since 1985, the annual average temperature has exceeded the long-term average (Meadow et al., 2019). Due to climate change, by 2100, the average daily maximum high is projected to increase from a 1960-1990 observed average of 84°F to 88.1°F under a low-emissions scenario and up to 92.7°F under a high-emissions scenario, as shown in Figure 1 (U.S. Climate Resilience Toolkit, n.d.). Days with a maximum temperature above 100°F are projected to increase from a 1960-1990 observed average of 49 to 101 under a low-emissions scenario and up to 139 under a high-emissions scenario by 2100 (U.S. Climate Resilience Toolkit, n.d.). Tucson is already the third fastest warming city in the U.S., with temperatures increasing 4.5°F since 1970 due to both climate change and continued development exacerbating the UHI effect (Climate Central, 2019).

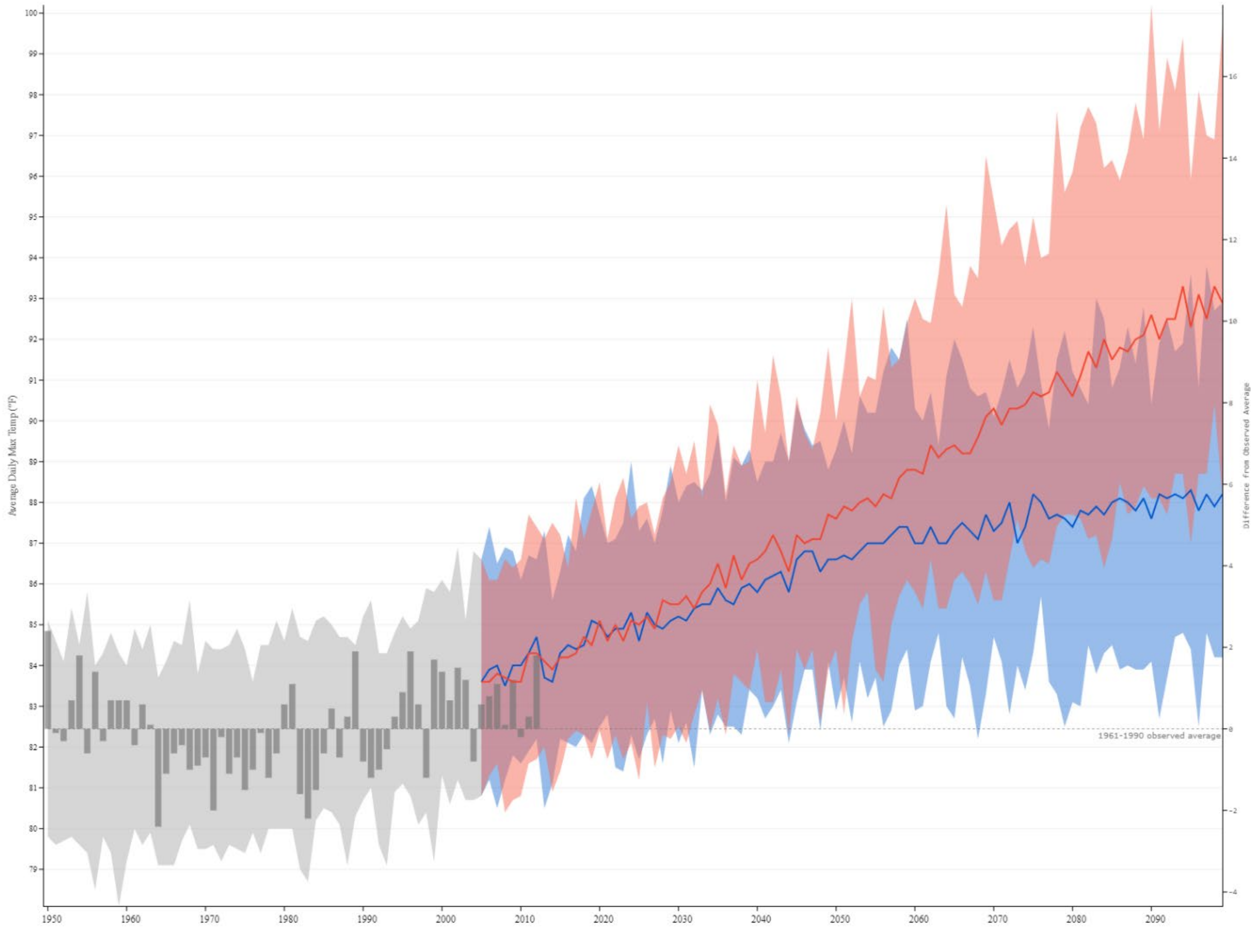

Figure 1 Historical and projected average daily maximum temperature for Pima County, AZ. (Source: The Climate Explorer)

3.3 COOL PAVEMENT PRODUCTS

Cool pavements are pavements or reflective coatings that are typically implemented on existing paved areas to help reduce associated UHI. The aim of cool pavements is to store less heat than traditional pavements, resulting in lower TS during the day and less heat released during the night (US EPA, 2014). There are a variety of cool pavement products that use different approaches to mitigating heat. Permeable pavements do this by increasing the porosity of a traditional pavement and/or using water to promote evaporative cooling. Evaporative pavements have additional benefits, such as reducing urban flooding, improving water quality, and increasing vegetation when vegetated pavers are used (Qin, 2015). Reflective pavements and coatings often have higher albedo, or higher reflectivity, which reduces the amount of heat stored within the pavement. While cool pavement coatings that are very light can mitigate heat, they can also reflect solar radiation onto pedestrians or nearby buildings, thereby reducing human thermal comfort for those walking on the pavement and increasing building energy use (Middel et al., 2020). Although the variety of cool pavement products currently on the market today all have costs and benefits, the easiest products to implement are often the reflective coatings, as they do not require the removal and replacement of existing pavement.

High-albedo pavements or treatments work by reflecting heat to develop an energy balance to ensure that the pavement does not have a higher heat concentration that negatively impacts human thermal comfort. High-albedo treatments, therefore, impact both TS and TA. TS is simply the temperature of a specific surface, while TA is the temperature existing in a space. With an effective high-albedo cool pavement TS should be reduced, subsequently reducing the TA. Within a lab setting, it has been found that pavements and pavement coatings with high albedo effectively reduce TS, but it is currently unclear as to how well these products impact TA (H. Li, Harvey & Kendall, 2013). For further information about the range of cool pavement products, we suggest the reader visit the Cool Roadway Partnership[1]. Notably, our project partner, the City of Tucson, is part of the Cool Roadway Partnership.

Studies in Laboratory Settings

Cool pavement products are typically well-tested within laboratory settings prior to going on the market (Table 1). For example, one such controlled lab experiment sought to understand the ability of heat-reflective pavement coatings to reduce the UHI effect by increasing the albedo of the surface (H. Li, Harvey, Holland et al., 2013). The experiment measured the TA, the TS of the different pavement materials, and the internal temperature of the different pavement materials. Measurements were taken with different instruments including thermometers, infrared thermal camera and thermocouples, respectively.

Table 1 Summary of studies on cool pavement products

Study	Type of pavement / application	Primary mechanism	Measures of study	Nature of control
Lu et al. (2022)	Heat-reflective pavement coating used on both concrete and asphalt	Albedo	Surface temperature, air temperature, internal temperature of pavements	Pavement use, pavement size, inside at all times
Li et al. (2013)	Asphalt, concrete and interlocking concrete	Albedo and pervious surface	Surface temperature, albedo	Pavement use, pavement size
Chen et al. (2019)	Reflective coating	Albedo	Albedo, internal temperature	Pavement use, weather conditions,

[1] Hosted by the Global Cool Cities Alliance, https://globalcoolcities.org/cool-roadways-partnership

				pavement size, inside at all times
Pisello et al. (2014)	Gravel of different grain sizes	Albedo	Albedo, surface temperature	Pavement use, pavement size

Cool pavement product in-lab evaluations allow for controlled conditions. However, the simulation of heating may or may not transfer to real-world conditions. For example, Lu et al. (2022) simulated heating with a halogen lamp in a humidity-controlled tank to evaluate a heat-reflective coating that was supplied by Decorative Paving Solutions. The experiment was controlled in several key ways. First, concrete and asphalt pavements were fabricated for the experiment (new pavement without prior use or wear). The experiment also controlled for the size of the samples—concrete samples included 6-by6-by20-inch slabs that were broken in half, and asphalt cylinder samples were 5 inches high with a radius of 3 inches. Pavements in the real world vary in depth, age, wear, and exposure to the elements.

Experimental designs in the lab also have different constraints. Studies, for example, do not test the long-term effectiveness of the cool pavement application, only measuring the thermal effects before and shortly after application of the cool pavement product—such as two hours after installation (Lu et al., 2022). While weather conditions, such as wind or humidity, were tested in a tank, real-world realities of pavement, like cars driving, people walking, weather exposure near cracks or broken pavement, and other real-world conditions and their effects over time are not typically part of experiments. Lu et al. (2022) found that the cool pavement product did not perform well in windy conditions, noting that cool pavement products would be most effective in cities where there is a lot of direct sunlight, such as Phoenix and Los Angeles, while not being efficient in cities with constant wind, such as Chicago. Similarly, performance of the product in shade, different use settings, or age of road was out of scope.

In one experiment by Chen at al. (2019), the authors explored the impacts of varying albedo levels inside a laboratory setting by using different types of pavement textures treated with different types of reflective pavement coatings. The pavement samples were placed in a box of plexiglass that was lined with a black cloth that had high solar absorption, located indoors with an infrared lamp simulating the conditions of solar radiation. A dual pyranometer was used to record “incident” and reflected solar radiation. The authors measured internal temperature of the slabs using a resistance thermometer, recording four temperatures taken at different depths, and TS measured every minute for an hour. The temperature as well as the surface reflectance were recorded every minute for an hour. The slabs created for this study had a variety of textures applied to them (Smooth, Rough, and Very Rough) and were also coated with different reflective coatings (Nano-TiO2, Micro-TiO2 and Nano-ZnO) at different thickness (0.3, 0.6, and 0.9 kg/m^2). Chen et al. (2019) found that the texture had little effect on overall temperature, though the rougher surfaces reflected less solar radiation and, therefore, had a slightly higher temperature. They also concluded that these reflective compounds are most effective at cooling the pavement surface, ranking Micro-TiO2 as having the greatest cooling effect followed by Nano-Zn and Nano-TiO2. Although the authors suggested coatings using Micro-TiO2 can be effective, they point to a need for further testing to determine whether the improvements may influence the durability or effects on aging real-world pavements.

Our Study: PlusTi Treatment

In this study, we evaluate the implementation of the Pavement Technology Inc (PTI) PlusTi asphalt rejuvenator in a real-world application through Tucson's pilot project[2]. PlusTi implements titanium dioxide (TiO2) into its mixture, which is used to make a variety of reflective products from road stripes to sunscreen. When applied to a surface TiO2 reflects UV rays, which helps prevent the absorption of heat associated with UV into the existing pavement.

The PlusTi product is currently being used in Austin, Charlotte, Cincinnati, Orlando, Raleigh, and many other U.S. cities. PTI states that PlusTi projects have a targeted Solar Reflectance Index (SRI) reading of 40, as most roads have an SRI reading of 5 to 10. PTI suggests an expected improvement in air temperature by 5°F to 7°F and that PlusTi reduces vehicle-associated volatile organic compounds (VOCs) and nitrogen oxide (NOx) by up to 60%, which supports improved air quality and less trapped heat within an UHI. While our study focuses on heat and human comfort, we note the potential air quality improvements with PlusTi because it is somewhat unique to this product. Measuring the impacts on air quality within this real-world experiment was out of scope for this project.

The PlusTi asphalt rejuvenator is applied to existing pavements as a yellow-brown compound. Once set for about one hour, it penetrates the road and is indistinguishable from standard pavements. One of the advantages of this product is that it does not obstruct or discolor previous road markings, so there is no need to restripe, unlike many cool pavement products. Moreover, as this product is an asphalt rejuvenator, the pavement will absorb less heat and reduce oxidative damage, theoretically extending the life of the road. In this study, we aim to capture human-scale comfort—such as what is experienced by pedestrians, cyclists, or those waiting for transit. While there may be a need for real-world experiments evaluating the impacts of this kind treatment on the duration of pavement life span, these measurements are out of scope for this project.

Ultraviolet (UV) Radiation Exposure (Exploratory)

Although we provide an extended literature review working paper in Appendix A, ultraviolet (UV) radiation exposure was not originally part of the proposed experiment measuring the impacts on human comfort. However, after the application of the cool pavement treatment at Tucson's pilot location, we received several public comments requesting more information about the potential impacts on UV radiation exposure. In response, we decided to capture some measurements of UV during our second field experiment and incorporate an initial review of UV radiation as it relates to human comfort and transportation infrastructure. Any lessons learned from the UV portions of

[2] https://www.pavetechinc.com/plus-ti/

this study should be considered “exploratory” and subject to future research or more controlled measurement or experimentation.

We conducted a Google Scholar literature search on the effects of UV radiation exposure to humans in urban environments, including combinations of the search terms: UVA or UVB, and Exposure, Skin Cancer, Tree Canopy, or Urban Environment. In this search, we identified 15 relevant articles from the past 20 years (2002-2022). The most prominent theme within the articles was the role of vegetation and urban tree canopy in mitigating UV radiation exposure. Specifically, seven articles (47%) discussed the efficiency of tree placement and the geometry of the exposure to make a proper canopy (Bowler et al., 2010; Grant & Heisler, 2006; Langenheim et al., 2020; Levinson & Akbari, 2002; J. Li & Liu, 2020; Na et al., 2014; Parisi & Turnbull, 2014). These articles discussed the importance of tree cover to mitigate overexposure, three of which discussed UVB exposure (Grant & Heisler, 2006; Na et al., 2014; Parisi & Turnbull, 2014). The placement of the trees to create a proper canopy is generally thought to be more important than having a high density or number of trees in an area (Langenheim et al., 2020).

While pedestrian exposure is of high interest to the research team, only three articles (20%) discussed the impacts of UV radiation exposure while engaging in physical activities such as bicycling (Kimlin et al., 2006; Serrano et al., 2010). One evaluation of sports activities investigating 144 different Olympic events found that the most UV radiation exposure is seen in women’s tennis singles, men’s golf, and men’s cycling road races (Downs et al., 2020). In these articles, mitigation strategies often included user-driven solutions, such as wearing athletic clothing. Further, these articles discussed how well-shaded parts of the body, such as legs, are still exposed to too many UV rays. For example, one article noted that cloud cover does not provide enough protection from UV rays, and many residents of urban areas are still at high risk of overexposure during cloudy days (Grant & Heisler, 2006).

4.0 STUDY DESIGN

This study aims to capture the effects of the City of Tucson's pilot project application of the PlusTi treatment using a natural experiment design. In this study, we collected TS, TA, and human thermal comfort as approximated by WBGT. We also collected UVA/UVB as an exploratory pilot study. In this section, we discuss the before-after and case-control nature of this study, including the timing of data collection and site selection. We then describe the data itself and the different types of heat-related measurements we collected. Following, we summarize the methods used to analyze the different types of data.

4.1 BEFORE-AFTER & CASE-CONTROL

Cool pavements are often well-tested in laboratory settings but less studied in real-world settings. This is partly due to both the newness of the products and the difficulty of controlling for conditions in natural experiments. In this study, we attempt to compare measurements using a two-pronged approach:

- **Before-after (or pre-post) intervention or treatment:** Taking similar structured measurements both before and after treatments at the same locations and using the same protocols, selecting a time of year with similar weather patterns (e.g., solar noon, expected highs/lows).
- **Case-control comparisons:** Taking similar measurements at treatment locations and similarly situated "control" location while using the same protocols.

In this study, we anticipated the need to control for both built environment factors (street types, surrounding land use, greenspace along the street) and weather variability. The City of Tucson pilot study had previously identified a stretch of urban road to apply the treatment. Therefore, we used a GIS-informed approach to identify a comparable "control" area with similar built environments to the treatment areas to serve as a valid case-control. While collecting data both before and after treatment, we aimed to select data collection days to control for variations in weather by selecting data collection weeks in fall and spring with similar approximate day length and expected weather matched. Each of these considerations is discussed in more detail below.

Temporal and Weather Considerations

Timing the data collection required a balance of considerations across the research team, the city, vendor, and the weather. Decisions around data collection timing had to incorporate vendor availability, City of Tucson funding calendars, the NITC award funding cycle, and the availability of student workers to assist with data collection. Further complicating matters, Tucson's hot season is long but includes a distinct monsoon with more humid conditions and variable cloud cover and rainfall. In an ideal world, weather conditions—including TA, sun angle, and day length—would be equal for data collection before and after treatment. To plan for this, we decided to target the before-treatment data collection during fall 2021 and the after-treatment data collection during late spring 2022 (see subsection below). In addition, we prioritized mid-day collection to capture the highest heat of the day. Finally, we wanted centerline road temperature data and thus needed to close traffic lanes in partnership with the City of Tucson. For both safety considerations and to minimize traffic disruption, we limited data collection to weekends.

The NITC grant was not finalized until October 2021, just as temperatures in Tucson began to cool off. In response to the temporal limitations described above, pre-intervention data were collection on October 16, 17, and 23 of 2021. The cool pavement product was then applied by the vendor on December 15, 2021.

To have an effective post-treatment observation period, we needed to anticipate the match for the approximate weather patterns and sun conditions of the pre-testing dates. Table 2 demonstrates that mid-October and early April are rough matches for historic average temperature and day length, even if temperatures are higher for shorter days in the fall than in the spring. Using this information, the team choose April 2, 3, and 10 as post-intervention data collection days. We anticipated and accounted for variations in TA between weather stations and what would be observed at each study site due to differences in weather patterns across the larger Tucson region, differences in microclimates, and differences in weather station equipment and devices used within this study to collect data.

Table 2 Mid-October and early-April weather patterns (NOAA)[3]

Dates	Historic Average Temperature (High/Low) (℉)	Actual Temperature (High/Low) (℉)	Solar Noon (hh:mm:ss)	Day Length (hours)
October 16th, 2021	72.6 (86/59)	78.0 (92/64)	12:09:14	11.37
October 17th, 2021	72.3 (86/59)	75.5 (89/62)	12:09:02	11.32
April 9th, 2022	66.7 (82/52)	76.5 (92/61)	12:25:19	12.78
April 10th, 2022	66.9 (82/52)	76.5 (88/65)	12:25:03	12.82

See Table 3 for the final list of data collection periods. It is worth nothing that, in addition to the observation periods included in this table, the study team explored collecting data during the evenings and mornings following several data collection days. Although the purpose of this study is to evaluate the impacts of human comfort—specifically pedestrians and cyclists near roadways—we recognize that a major influence of cool pavement technologies includes the ability to allow pavements to cool faster by reflecting the radiation that would otherwise be absorbed by the pavements. Because these observations were out of scope, we have left these data out of the current report and aim to analyze and discuss these data in our future work.

[3] https://www.weather.gov/wrh/Climate?wfo=twc

Table 3 Summary of study data collection time periods

	Daytime Data Collection
Before-Treatment Observations (October)	
October 16, 2021	10:00 AM - 4:00 PM
October 17, 2021	10:00 AM - 4:00 PM
October 24, 2021	10:00 AM - 4:00 PM
After-Treatment Observations (April)	
April 2, 2022	10:00 AM - 4:00 PM
April 3, 2022	9:15 AM - 3:00 PM
April 10, 2022	9:20 AM - 3:00 PM

Notes:
Data collection periods reported may vary from those analyzed. For example, due to the nature of natural experiments, the set-up and take-down time across different sites and days varied, and during the April months, the permit for disrupting traffic only extended to 3:30 PM. During analysis, we constrained our review to consistently measured and synced time periods (such as the 10:00 AM—3:00 PM daytime data collection period).

Site Selection and Controlling for Built Environment

After the timeline for before-and-after study observations was determined, we then conducted a site selection analysis to identify reasonable control locations while controlling for factors in the built environment. The treatment location was selected by our partners at the City of Tucson, driven in part by their own programming of pavement fog seal applications and corresponding corridor improvement funding related to the Parks and Connections Proposition 407 approved by voters in 2018. The cool pavement treatment was applied to the north-south Country Club Road from south of Broadway Boulevard through Aviation Parkway in December 2021.

To better understand our treatment area, we divided the 1.7-mile stretch of Country Club Road into three segments (see Table 4 and Figure 2) accounting for the different road typologies, such as number of lanes, width of roads, existence of sidewalks and surrounding land uses. North Reid was near larger vehicle parking lots with property walls near the roadway with stucco and concrete, and households near North Reid were also higher income. The Reid segment was between a residential area and the largest midtown urban park, Reid Park, with mature trees, lawns, and sidewalks. The South Reid segment has a narrower roadway with some block walls and fewer tree shade or greenery. Households neighboring South Reid were lower income compared to the other two segments.

Table 4 Country Club Road corridor segment receiving cool pavement treatment

Segment	Vehicle Lanes	Bicycle Lane	Sidewalks	Land Use
(A) North Reid	Four lanes	No	Yes	Residential
(B) Reid	Four lanes with center turning lane	No	Yes	Half Residential, Half Public Park
(C) South Reid	Two lanes	Yes	No	Residential
Notes: Segments (A, B, C) are annotated in the map show in Figure 2.				

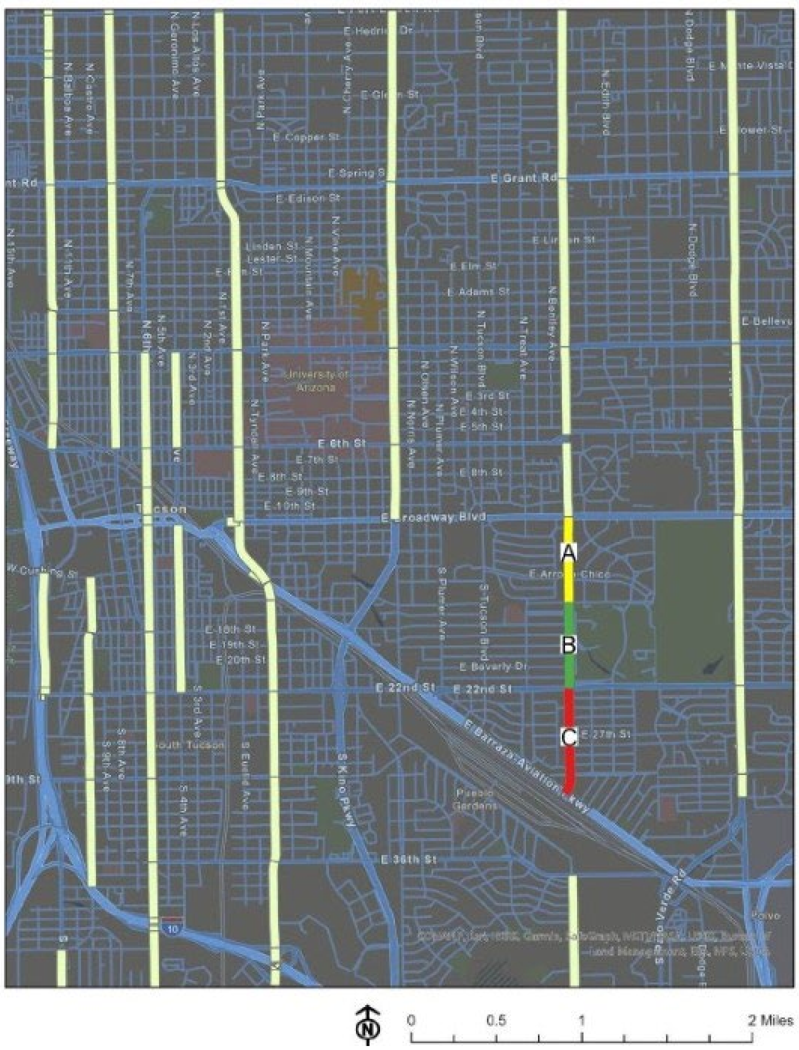

Figure 2 Map of cool pavement treatment locations along Country Club Road including segments labeled (a) North Reid, (b) Reid, and (c) South Reid with yellow facilities noting potentially comparable north/south transportation facilities

To select control sites (also referred to as “comparison” or “no treatment” locations), we also compared land cover profiles[4] from data obtained from Pima County’s open data repository[5] and compared the three segments of Country Club Road to 162 candidates for roadway segment controls. Intersections, small segments, and other roadway features that may affect subsequent statistical analysis were removed.

All east-west roadways are removed so that only centerlines match the north-south orientation of the treatment location. Based on the characteristics identified in Table 4, we then identified any potential north-south transportation roadways with similar characteristics that would allow us to compare with treatment roadways. We calculated Euclidean distances between controls and treatment locations, prioritizing locations that were located closest to the treatment. Finally, manual inspection of treatment and candidate controls were conducted to select the most similar comparison locations for each segment.

Our final control locations include:

- North Reid treatment area control includes Country Club Road immediately north of the treatment area, just across Broadway Boulevard from the treatment site, and is of almost identical width.
- Reid treatment area control includes Swan Road between Grant Road and Fort Lowell Road. This control location is slightly wider than the treatment site (68’ vs 60’) and has a lower percentage of tree canopy cover (16% vs 22%) with slightly larger impervious surface percentage cover (48% v 40.5%).
- South Reid treatment area control is located on Country Club Road between Benson Highway and Bilby Road. Although the control location is of identical width, it has a slightly greater percentage canopy cover than the treatment area (17.7% vs 13.5%).

In choosing the location based on relative condition and built environment, other elements were de-emphasized. For example, we were not able to consider the composition of the pre-existing pavement, meaning that different areas along the pilot test could be made up of multiple layers over the years, resulting in different thermal properties. Orientation of the pilot ended up as a north-south street, requiring all additional “control” sites be north-south. Within this 1.5-mile stretch of road, other built environment features varied,such as road width, tree canopy, block walls along the streets, and (un)paved land areas on private residential land. During the manual inspection of candidate sites, we attempted to control for these differences when selecting our data collection locations even within the different treatment/control locations.

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[4] The seven land cover classes used in this study are: Water; Trees/Shrubs; Irrigated Land; Desert; Barren/Bedrock; Impervious; and Structures.

[5] This analysis uses the County’s 2018 Land Use/ Land Cover raster to build land cover profiles of test sites. The 2018 Land Cover/ Land Use raster has a spatial resolution of 2ft and is derived from 2015 NAIP imagery, LiDAR, and the County’s orthophoto collection. Streets are mapped using the County’s Major Street Centerlines feature layer. Street centerlines are downloaded from Pima County and mapped in ArcGIS Pro.

Lastly, for each of the three treatment roadway segments (North Reid, Reid, and South Reid), we selected two data collection locations, where we periodically label Treatment 1 or Treatment 2 in our results and discussion.

4.2 DATA: MEASURING HEAT

Surface Temperature

TS is defined as the temperature of a specific surface. Different surface and pavement types absorb and radiate the stored heat throughout the day, increasing the overall TA and thermal discomfort within the area. TS can be measured through several different methods and are typically recorded using °F (as in this report) or °C. Approximations of TS can be obtained through satellite imagery and combined to create land surface temperature maps at a larger scale, but can also be collected at the site scale using field instruments such as infrared thermometers.

For this study, field measurements were conducted at each site during the study observations using a Delta Track ThermoTrace in °F (see Figure 3). At the top of each hour, the TS of each identifiable surface type along the corridor, measuring in both the sun and the shade on both sides of the corridor, including sidewalk, road, vegetation, middle-lane of road, and gravel. For each surface type, sun/shade, and side of roadway.

Figure 3 Delta Track ThermoTrace device being used to collect surface temperatures

Ambient Air Temperature and Wet Bulb Globe Temperature

TA can be likened to room temperature, as it is the temperature of the air in each area. TA tends to be a closer approximation of thermal comfort than TS. While thermal comfort is the overall level of heat stress experienced within one's environment, it is externally influenced by the TA, humidity, TS, and wind speed.It can also be impacted by one's clothing insulation and their body's metabolic rate. One way to approximate thermal comfort is through WBGT, an index determined based on the combination of TA, humidity, wind speed, and radiant heat measurements.

As explored in the background section, cool pavement products mainly increase reflectivity to reduce the heat absorbed and retained in pavement. One concern in practice is whether increasing reflectivity might also increase temperatures felt and experienced by pedestrians and cyclists. By capturing both TA and WBGT, we aim to assess if the thermal comfort of the most vulnerable road users is impacted.

For this study, field measurements were conducted at each site during the control and application periods. Kestrel Heat Stress Trackers were used to take TA and WBGT in °F throughout the day (Figure 4). There were usually three Kestrels present at each data collection location, one located in the center lane of the road and one along each sidewalk. The TA and WBGT measurements were collected at 10-second increments, which were then averaged for each (a) minute for regression analysis and (b) hour for summary comparisons.

Figure 4 Kestrels placed (left) alongside the road, (right) a Kestrel between a bike lane and sidewalk and, in the distance, a Kestrel in the center lane

UVA/UVB (Exploratory)

To better understand UV radiation exposure at large and the potential attribution of reflection off a cool pavement treatment, exploratory observations were collected to augment the evaluation during the April 2022 observations. In this study, we are evaluating PlusTi asphalt rejuvenator treatment, which contains titanium dioxide. Since titanium dioxide targets UVB, instruments to measure the UV Index and UVB levels were acquired—including the SolarMeter 6.5 which measures the UV Index (US EPA, 2015) and a SolarMeter Model 6.0 to measure UVB. These meters are developed to measure UV exposure in higher light environments (e.g., outdoors) with a full sky view (see Figure 5).

Figure 5 SolarMeter 6.0 (left) and Solar Meter 6.5 (right) https://www.solarmeter.com

Because the UV analysis was not part of the original study design, we collected data only at one location during the April 2022 observations. For the study area, data were collected at the east and west locations in the pedestrian right of way as well as the centerline measurement of the roadway with the cool pavement treatment applied on asphalt. At each location, UV Index and UVB readings were collected while holding the device pointed upwards (capturing direct UV from the sky) and downwards (capturing UV rays that may be reflected from the ground surface).

4.3 METHODS FOR ANALYSIS

As explored in the Background Section 3.3 Cool Pavement Products, there are several prior studies set in laboratory settings that evaluate cool pavement treatments as they related to TS and even internal pavement temperatures. Although those studies may not be able to systematically determine the impact of treatments on pavement durability, they are better able to capture the ability for these treatments to reflect heat, reducing the heat held by concrete or asphalt. In this study, we implement a natural experiment study design which introduces constraints and influencing factors not experienced in lab settings. As such, while we capture TS at an hourly basis at study locations in a systematic way, we are limited in our ability to speak statistically about the impact of cool pavement treatment on surface temperature (before versus after, or treatment versus control). Instead, our primary focus for this analysis is on TA and WBGT as indicators of human thermal comfort. Additionally, we reiterate that our UV radiation observations are only provided experimentally here and should be interpreted with caution.

Surface Temperature (TS)

TS was captured on the east, west, and centerline sides of each treatment and control location, for each type of ground cover (e.g., gravel/dirt, concrete, asphalt, grass) and for both sun and shade (where both are available). For each observation location, five measurements were captured at the top of each hour and then averaged. In this method, data collectors developed a system to capture TS at the same location throughout the day.

It is important to note that capturing TS at multiple locations and time periods is a manual data collection process in the field, and we are not currently able to capture TS as frequently as lab studies are able to instrument (e.g., observations every minute or so). In our analysis, we provide the trend of TS for each treatment and control data collection locations across the time of day. We limited our analysis here to "sun" observations, and we provide the before-and-after observations for each roadway segment. Further, we provide the TS values in degrees Fahrenheit and then we normalize the TS values in two ways: first, by the ambient temperature measured at the Davis Monahan Air Force Base (AFB) during the same hour of the same day of data collection and second, by the 11AM TS observations for the same location, day, and time.

Although we collected "shade" and "dappled shade" where available over the course of the day, the inconsistency of the shade availability introduces substantial noise in comparisons across locations. Further, we limit our analysis in this document to the treatment locations only—the asphalt road that did or did not receive the cool pavement treatment. In future work, we aim to explore the impacts of shade and dappled shade on temperatures of different types of ground cover throughout the day. Capturing TS in the real world frequently enough to control for variations in the movement of shade cover throughout the day, wind, or precipitation was not currently feasible with our available equipment and would be a fruitful area of future work. However, our data collection days included limited cloud cover, no precipitation, and only low speed winds (<5.5 miles per hour).

Ambient Air Temperature (TA) and Wet Bulb Globe Temperature (WBGT)

In the second analytical method, we consider two measurements of temperature that better capture human comfort: ambient air temperature (TA) and wet bulb globe temperature (WBGT). To evaluate effects of the cool pavement treatment before and after application, we estimate two sets of linear regressions predicting TA and WBGT collected using the Kestrel data collection tools and processes. In this analysis, our main variable of interest is the before-and-after variable—marking the data collection prior to cool pavement treatment (October 2021) and after treatment (April 2022).

To simplify the analysis for this report, we include centerline and sidewalk measurements; only those from treatment sites within each segment; and only observations averaged to the minute between the hours of 10:00 AM and 3:00 PM. In early iterations of this analysis, we also tested and compared large sets of hypothesis tests comparing treatment measurement to control, before measurements to after, and treatment measurements normalized by the control sites and/or airport locations. These hypothesis tests allowed us to explore different options for interpretating the data, but they did not allow us to control for other elements of the data collection (e.g., wind, shade).

We also test for overly correlated variables by estimating the Variance Inflation Factor (VIF) for each model; values of more than six indicate multicollinearity derived from highly correlated variables within the same regression. It is worth noting that interacted variables and temporal lags often derive higher VIFs and were accounted for by controlling for the relations between interacting variables[6].

For each location, we calculate the time of day relative to solar noon for each data collection data. We convert the time relative to solar noon to "hours" to better interpret the coefficient, and we include both the linear time of day and squared time of day indicator to control for the non-linear warming effect from mid-morning (10:00 AM) to mid-afternoon (3:00 PM).

During data collection, the research team marked times in which Kestrels were located in sun, shade, or dappled shade at the top of the hour. In this analysis, we include the presence of shade at the site of the Kestrel (yes/no dummy variable) as a control variable. Additionally, we recognize that the presence of shade at the center line may correspond with the time of day and the angle of sun through nearby trees where present. We interact the shade predictor with the time-of-day variable to test for a corresponding relationship. Furthermore, although all observation days had relatively low wind speeds, we include wind speed in miles per hour as a control variable as well.

In all four models, we controlled for the TA reported at the Tucson International Airport. We selected the data collection weeks in October and April because the solar noon was comparable during both time periods, which allows us to measure relatively similar times of the year both before and after the cool pavement treatment. However, we recognize subtle differences in the overall temperature from day to day and week to week require us to also control for the broader weather trends for the region. In this analysis, we tested different model specifications. We also consider normalizing (subtract or divide) treatment measurements by control-location measurement and airport TA. In all cases, the complexity of comparing models normalized by other measurements renders the regressions difficult to interpret.

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[6] The analysis was completed in R, the statistical programming software. VIF was estimated using the function "vif" in the package *car*. Interacted effects were considered setting the parameters *terms* as "marginal" and *type* as "predictor."

The minute-by-minute measurements at each of the six locations and two days result in highly significant autocorrelated residuals. In other words, the temperature measured at any one moment is highly correlated to the temperature measured the minute before, and possibly the minute(s) before that.

To test for temporal autocorrelation, we estimate the Durbin Watson (DB) Statistic for each model[7]. A DB statistic of “2” indicates no autocorrelation is detected. For models where autocorrelation is detected, we create spatial lags at one-minute intervals to include in the model. For each minute of observations, each of the N-number of lags represents the temperature detected at N-minutes before the observation occurred. For both TA and WBGT measurements, 15 regressions were estimated with one through 15 one-minute lag variables. For each model, we estimate the DB statistic to evaluate the presence of autocorrelation. In the results, we discuss the regression with lags associated with a DB statistic of two, indicating no significant amount of autocorrelation is detected. The results, therefore, explore the estimation four models predicting TA and WBGT measurements each (a) without temporal lags and (b) with lags.

In future work, we will incorporate controls for sidewalk measurements and control (“no treatment”) locations in the analysis. While the analysis presented in this report includes temporal lags to reduce temporal autocorrelation issues, future analysis will need to consider the spatial controls necessary to reduce spatial autocorrelation derived from cross-sectional measurements (e.g., east and west sidewalks and centerlines together).

UVA/UVB (Exploratory)

We collected limited data to explore any changes in UVA/UVB from the sky and from the roadway on different surfaces for one data collection site. While we do not statistically analyze this exploratory data in this report, we summarize what we observed here to document our method for future work. The potential risk of residents to UV radiation exposure due to cool pavement application was explored in a literature review and an exploratory field. This exercise sought to observe the reflective effects of a cool pavement solution and compare it with the pedestrian right of way.

[7] Test was completed using the Durbin Watson Statistic estimated in the R-software function “durbinWatsonTest” in the package *car*.

5.0 RESULTS & DISCUSSION

We have separated our results into three sections that align with the three different types of data we collected. First, TS examine the performance of the PlusTi asphalt rejuvenator in a real-world application. TA and WBGT allow us to consider the impacts of the cool pavement product on thermal comfort. Finally, exploratory UVA/UVB data are summarized for information purposes only.

5.1 SURFACE TEMPERATURE (TS)

While we report our TS observations, much more work is needed in refining a natural experiment study design that allows for surface temperatures to be captured frequently enough to explain the variation observed here. The TS observations are summarized in three different sets of images, one for each of the cool pavement treatment locations: Figure 6 North Reid; Figure 7 Reid; and Figure 8 South Reid. The comparisons we are making in each graphic include temperatures over the time of day (10:00 AM to 3:00 PM or 4:00 PM, marked on the graphic is hour 15 or 16 during the day). Each plot includes the data for both before and after the treatment, and each road segment includes two treatment observations and the comparative control. Following, we have considered both (top graphic) TS; (middle) TS difference from the Davis Monthan Air Force Base (AFB); TA for each day and hour of data collection; and (bottom) TS difference from the 11:00 AM TS measurement for that location and day. The "difference" was calculated by taking the TS observation and subtracting the normalized observation (either Monthan AFB TA or 11:00 AM TS measurement). It is worth mentioning that each observation on these graphics is an average of five observations taken in the field and then averaged. For all centerline observations as asphalt reported in full sun, we calculated 95% confidence intervals ranging from 0.12 to 1.41 ºF, suggesting a relatively small margin of error.[8] The margin of errors were removed from the graphic for simplicity.

Notably, the after-treatment observations suggested greater heat increases relative to before-treatment observations at both North Reid (Figure 6) and Reid (Figure 7). This may be an artifact of the slightly longer days and slightly later solar noon timeline of observations (see Figure 1), which also imply that the rising sun was likely above any tree shade generated on the east side of the roadway and, therefore, may have been radiating on the pavement for longer *after* treatment in April. The treatment and control locations for South Reid,the most exposed area of the cool pavement treatment area, saw very little difference in the hourly trend (Figure 8, bottom graphic), even with slightly longer daytime hours. Cool pavement technologies that reflect radiation from the pavement may have stronger impacts in encouraging the pavement to cool faster after the radiation has passed. The data collected here represents largely the TS during the primary temperature increases during the day, not the cool-off period.

We collected these data manually at the beginning of every hour, and the limited sample size prohibits our ability to control for contextual factors (i.e., using a regression

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[8] The margin of error was calculated by multiplying the Z-score (1.96) by the standard deviation of observations divided by the square root of five observations.

that controls for solar noon, wind speed) much in the same way we were able to in the TA/WBGT analysis (see following Section 5.2

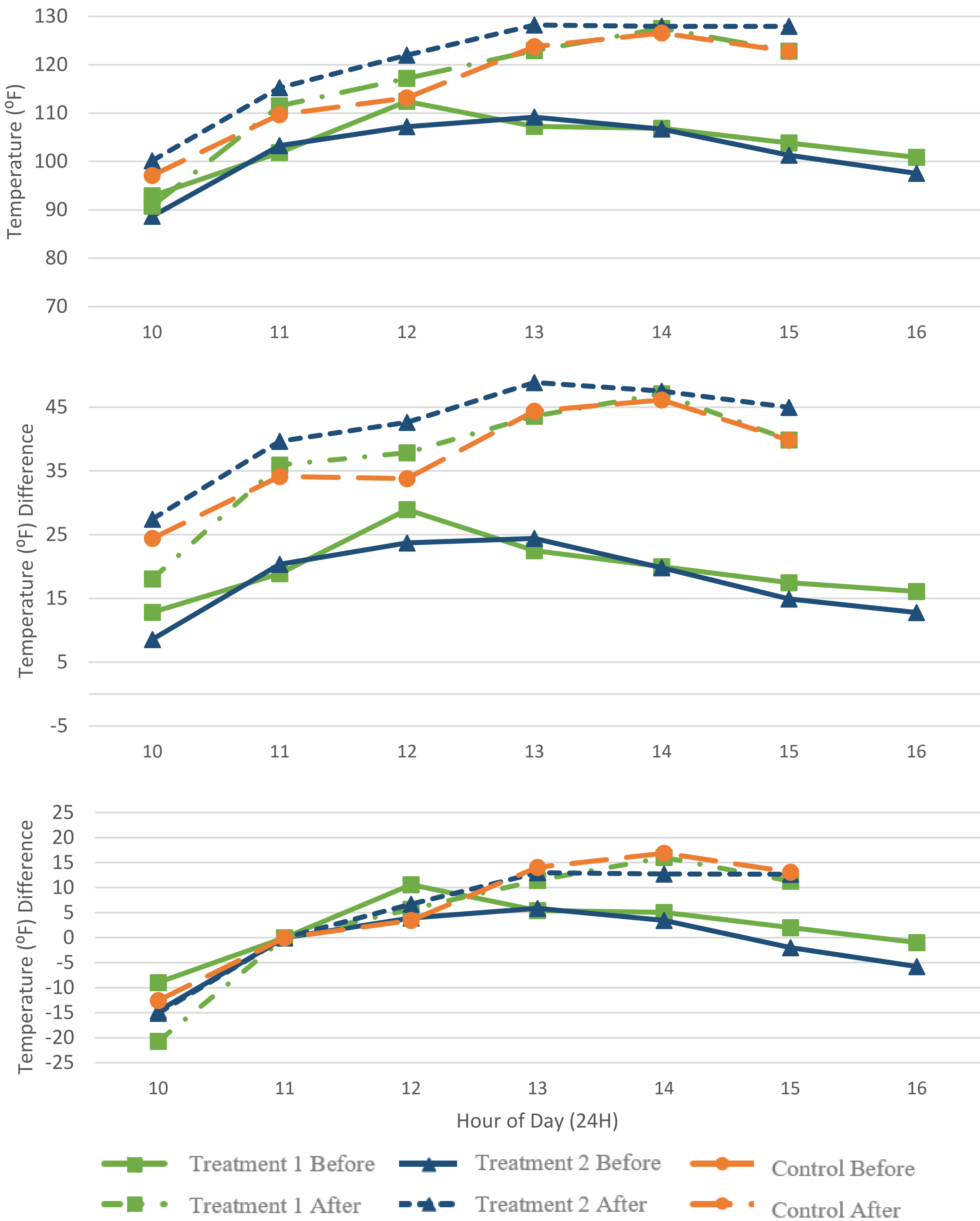


Figure 6 surface temperature measurements for North Reid segment before (10/17/2022) and after (4/3/2022) treatment including (top) temperature °F, (middle) temperature difference from Davis Monthan Air Force Base ambient temperature, and (bottom) temperature difference from 11:00 AM surface temperature

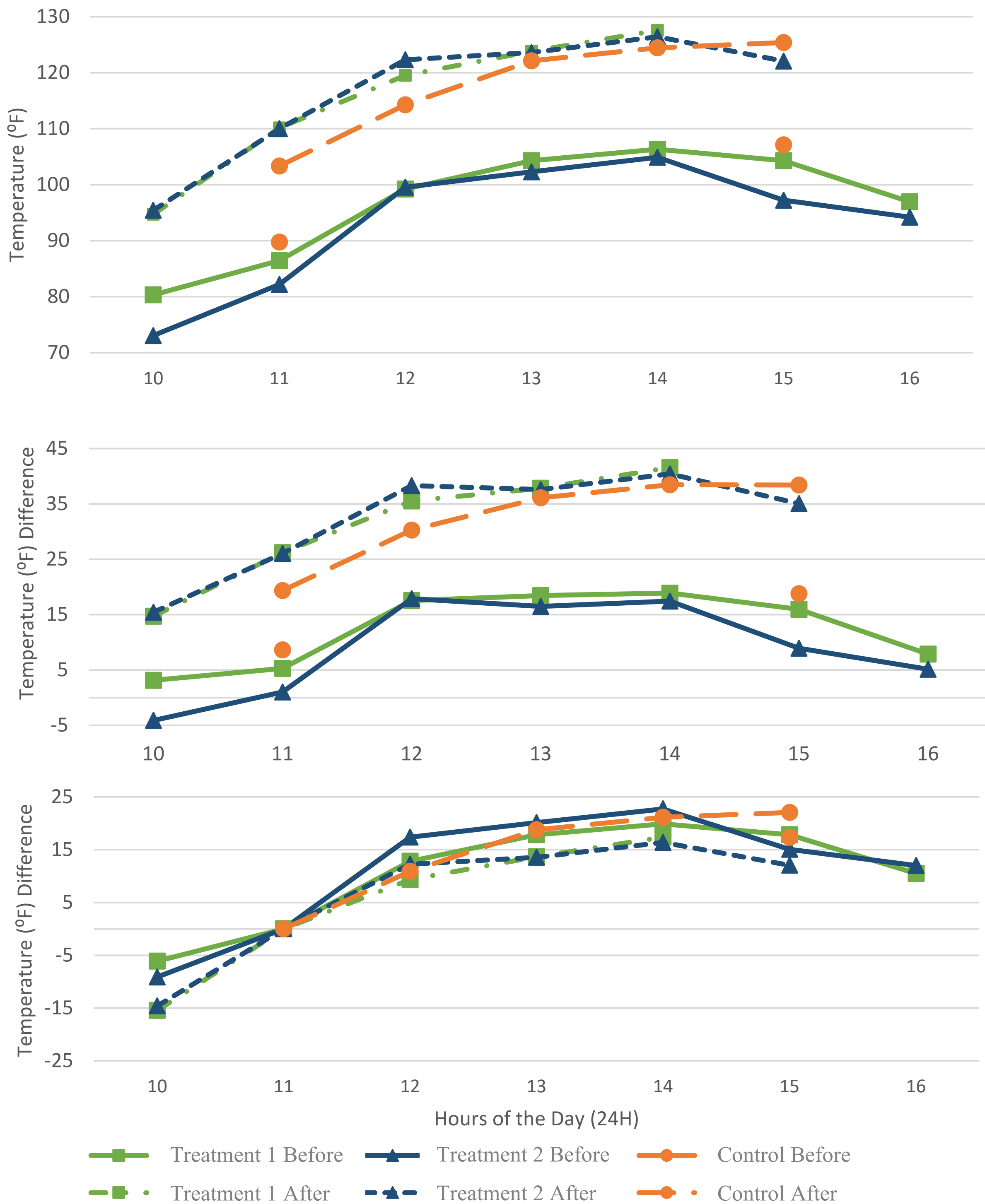


Figure 7 Surface temperature measurements for Reid segment before (10/16/2022) and after (4/2/2022) treatment including (top) temperature °F, (middle) temperature difference from Davis Monthan Air Force Base ambient temperature, and (bottom) temperature difference from 11:00 AM surface temperature

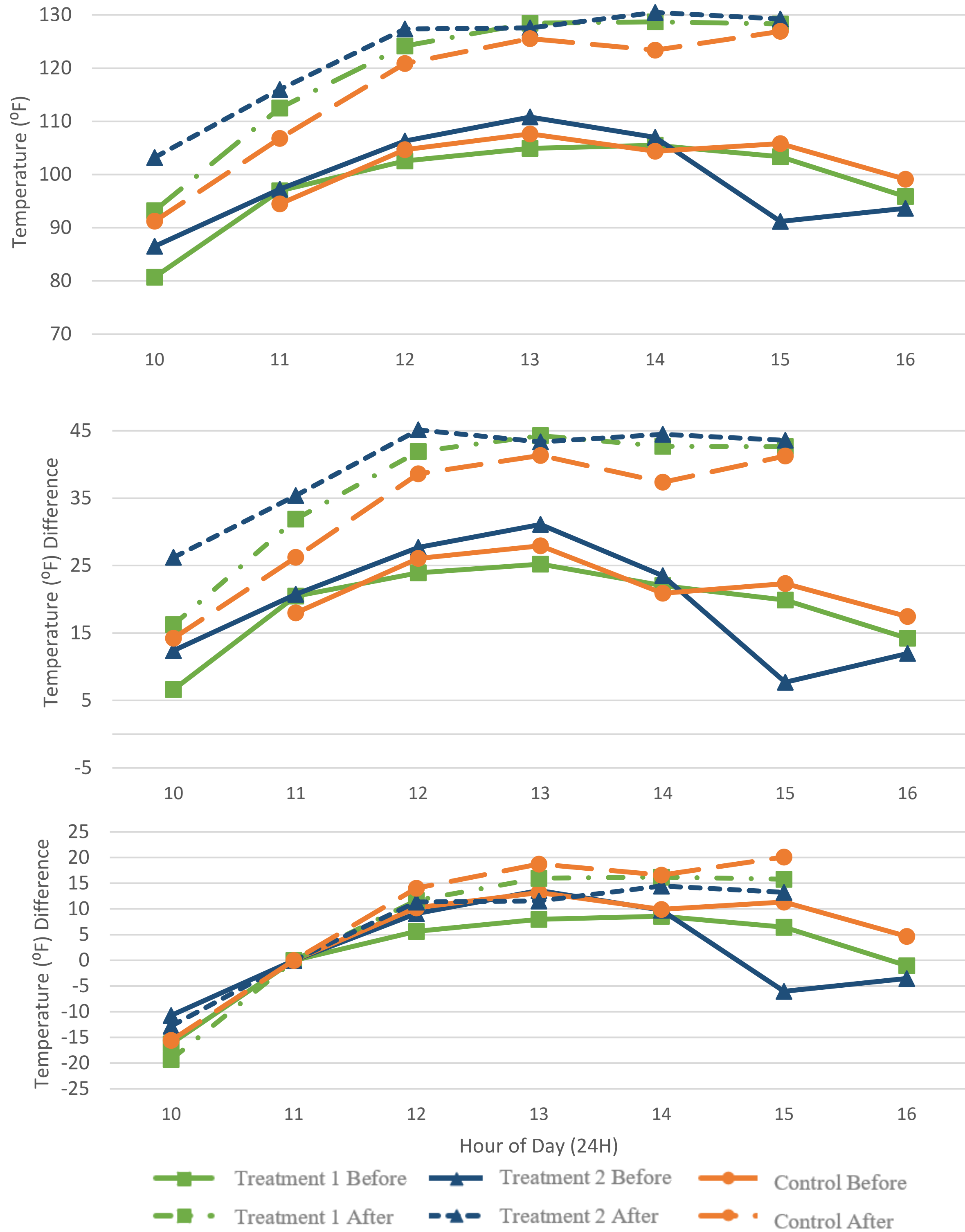


Figure 8 Surface temperature measurements for South Reid segment before (10/23/2022) and after (4/10/2022) treatment including (top) temperature °F, (middle) temperature from Davis Monthan Air Force Base ambient temperature, and (bottom) temperature difference from 11:00 AM surface temperature

5.2 AMBIENT AIR TEMPERATURE (TA) AND WET BULB GLOBE TEMPERATURE (WBGT)

Regression results are provided in Table 5. Before introducing the temporal lags, the variables included explain roughly 70% of the total variation in TA and 36% of WBGT measurements (adjusted R^2). The results are explored in the following subsections.

Table 5 Linear regression predicting ambient air temperature and wet bulb globe temperature (°F) (a) without and (b) with temporal lags

	(a) Without Lags				**(b) With Lags**			
	Ambient Air Temperature (TA) (°F)		**Wet Bulb Globe Temperature (WBGT) (°F)**		**Ambient Air Temperature (TA) (°F)**		**Wet Bulb Globe Temperature (WBGT) (°F)**	
Predictors	**Estimates**	**p-value**	**Estimates**	**p-value**	**Estimates**	**p-value**	**Estimates**	**p-value**
(Intercept)	27.72	<0.001	52.52	<0.001	6.32	<0.001	1.48	<0.001
Segment and Site								
North Reid 1	base case		base case		base case		base case	
North Reid 2	-0.58	<0.001	-1.52	<0.001	-0.20	<0.001	-0.05	0.002
Reid 1	-0.81	<0.001	-2.05	<0.001	-0.19	<0.001	-0.05	<0.001
Reid 2	-0.95	<0.001	-1.39	<0.001	-0.07	0.103	-0.02	0.119
South Reid 1	0.63	<0.001	0.27	0.003	0.22	<0.001	0.02	0.192
South Reid 2	-0.69	<0.001	-0.52	<0.001	-0.10	0.027	-0.01	0.627
Wind (mph)	-1.57	<0.001	-0.50	<0.001	-0.97	<0.001	-0.04	<0.001
Airport Ambient Temperature	0.76	<0.001	0.30	<0.001	0.27	<0.001	0.01	<0.001
Lags								
1 minute					0.70	<0.001	1.61	<0.001
2 minute							-0.83	<0.001
3 minute							0.19	<0.001
Time minus Solar Noon								
Hours (time - solar noon)	0.33	<0.001	0.36	<0.001	0.06	0.002	0.00	0.902
Hours-Squared	-0.26	<0.001	-0.34	<0.001	-0.11	<0.001	-0.02	<0.001
Presence of Shade								
No Shade	base case		base case		base case		base case	
Shade	-1.02	<0.001	-2.68	<0.001	-0.31	<0.001	-0.08	<0.001
Shade * Hours	0.03	0.599	0.27	<0.001	-0.01	0.858	0.01	0.299
Before/After								
Before								
After	0.54	<0.001	0.30	<0.001	-0.27	<0.001	-0.01	0.234
Observations	10,830		9,690		10,792		9,588	
R^2 / R^2 adjusted	0.707 / 0.706		0.365 / 0.365		0.879 / 0.879		0.98 / 0.98	

Temporal Effects (Time of Day, Temporal Lags)

The temporal effects are examined in two ways: by the hour of the day relative to the day's solar noon (both linear and squared) and by the temporal lags. Without the temporal lags, both the linear and squared variables for time relative to solar noon were significantly related to both TA and WBGT. Together, they indicate the non-linear rise in temperatures in the morning intuitively and decline in the afternoon.

We estimated 15 regressions, each with an additional one-minute temporal lag, and tested for autocorrelation using the Durbin Watson (DB) Statistic. The DB statistic for each of the 15 regressions estimated are provided in Figure 9 and Figure 10 for TA and WBGT regressions, respectively. For the TA analysis, a single one-minute lag reduced the autocorrelation to be insignificant (DB statistic of about 2.0). This indicates that the measured TA is correlated with only a single previous minute. For WBGT, three one-minute lags were needed to remove the correlated residuals detected in the DB test statistic.

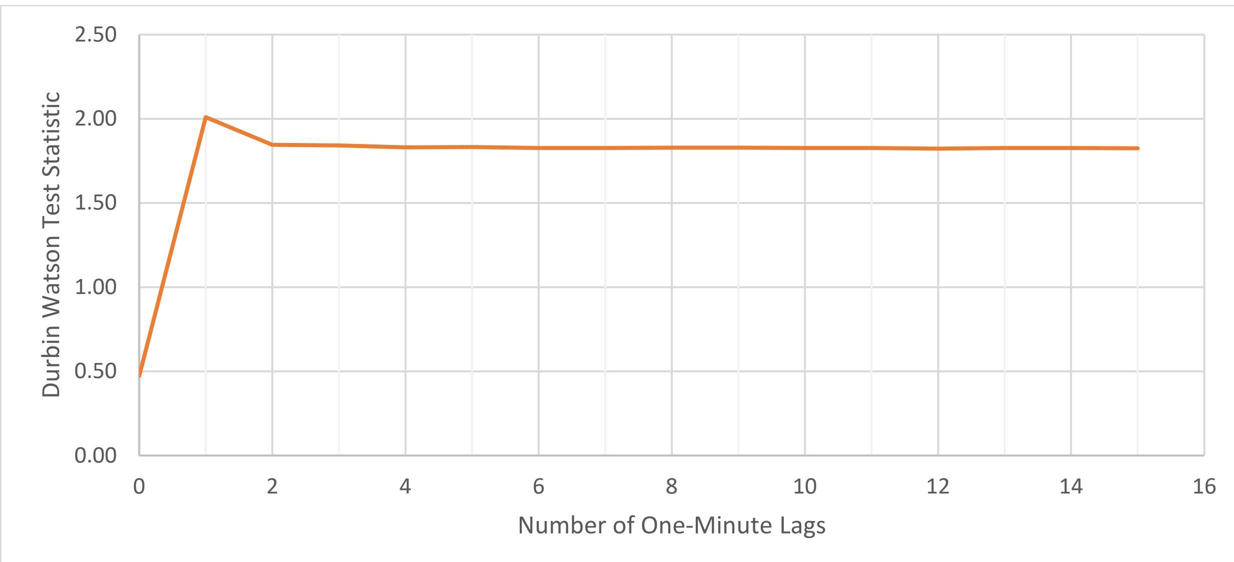


Figure 9 Ambient air temperature regressions by number of one-minute lags incorporated

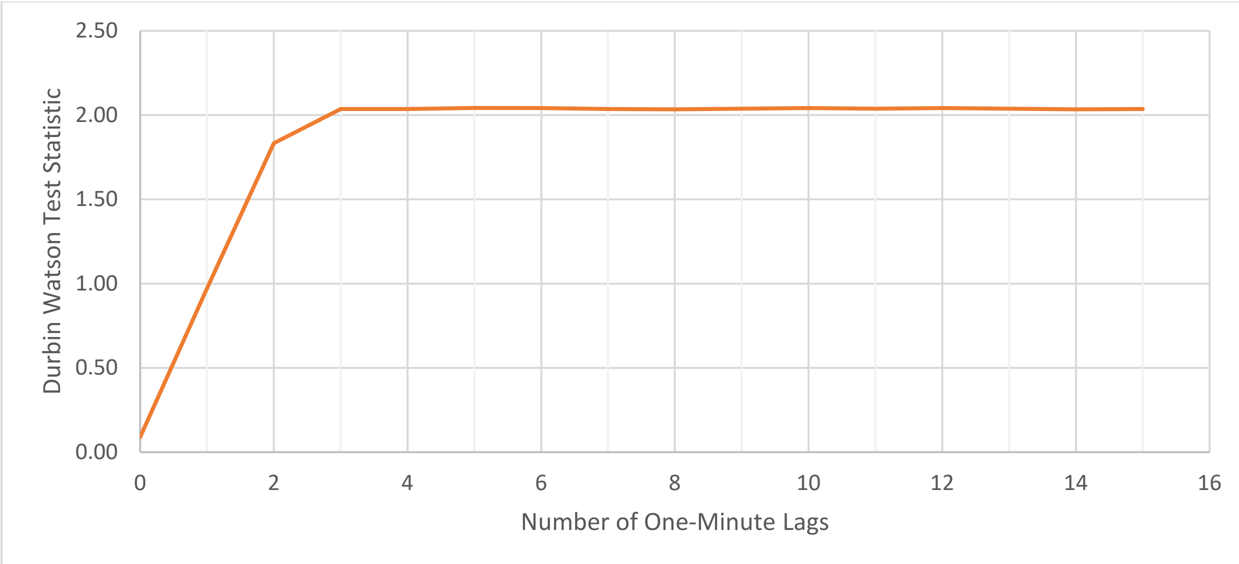


Figure 10 Wet bulb globe temperature regressions by number of one-minute lags incorporated

Segment and Sites

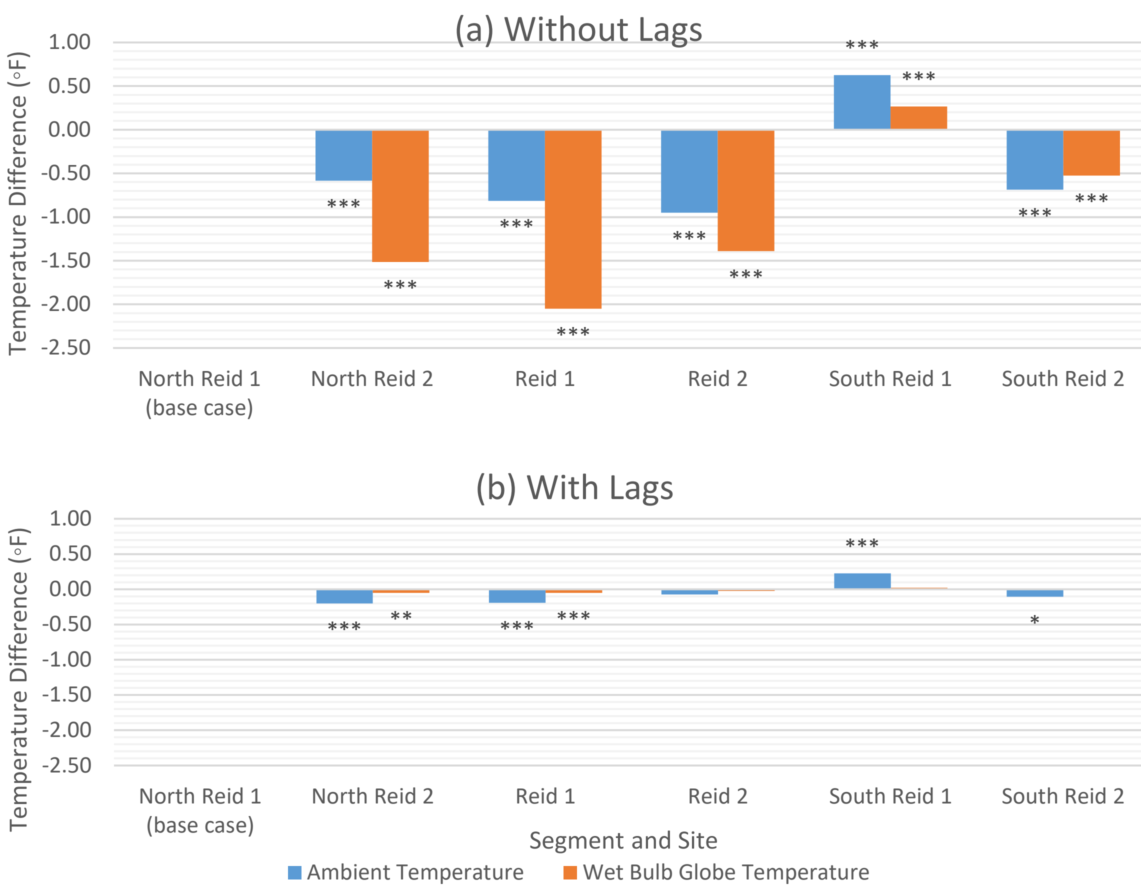
Although one might expect the airport temperature to be highly correlated with Kestrel measurements, we did not observe enough multicollinearity to indicate an issue. Observed TA and airport TA have a significant Pearson's correlation of 0.75, while WBGT has a significant 0.42 correlation with airport TA. In the regressions without the temporal lags, the Variance Inflation Factor (VIF) did not indicate issues with multicollinearity for either TA (VIF: 3.9) or WBGT (VIF: 4.0). After we introduce the lags, the VIF for both regressions increases slightly (Ambient VIF: 5.4; WBGT VIF: 4.2) but does not exceed the threshold indicating an issue (VIF > 6.0).

In all regressions, we control for each of the six data collection locations using dummy variables with the North Reid Treatment 1 location as the base case against which all other locations are compared. Both with and without lags, South Reid Treatment 1 is the only location estimated to be warmer than the base case, North Reid Treatment 1, but the significance is lost entirely for WBGT estimates once the lags are added. All other locations are estimated to be cooler than North Reid Treatment 1. North Reid 2 and Reid 1 and 2 locations are all closest to the large Reid Park area, suggesting locational effects of park-adjacent estimates. South Reid is the most barren landscape with the fewest trees and greenery, likely the explanation for the warmer temperatures. After controlling for temporal lags, the effect size and significance for locations on WBGT diminish in scale to nearly no difference in temperature. Only North Reid 2 and Reid 1 locations have statistically significant lower WBGT after lags are added, but at a small fraction of a degree (-0.05°F). After temporal lags are included, the impact of location on TA ranges from 0.07°F to 0.22°F.

Shade and Wind Speed

The presence of shade is also significantly and negatively related to both TA and WBGT (p-value < 0.001) with and without lags. However, once temporal lags are introduced, the effect size of shade diminishes, suggesting that the impact of shade is at least partly related to whether there was shade impacting the location in the minutes prior to the observation. Without temporal lags, the interaction between shade and hour of the day is also significantly related to WBGT, but this effect diminishes once temporal lags are introduced. The presence of shade corresponds with a 1.0°F or 0.3°F decrease in TA without and with lags, respectively. For WBGT, the impact of temporal lags is much greater. Shade is estimated to correspond with a 2.7°F decrease in WBGT measured without controlling for lags, but only a 0.08°F decrease once lags are introduce.

Wind is also significantly and negatively related to both TA and WBGT (p-value < 0.001) with and without temporal lags. For each one-unit increase in wind by miles per hour (MPH), TA decreased an estimated 1.6°F without temporal lags and 1.0°F with lags. As a composite measure, WBGT often takes longer to respond to changes in wind, humidity and shade. For each one-unit increase in wind by miles per hour, we observed a 0.5°F and 0.04°F decrease in WBGT without and with lags, respectively. It is worth noting that both October and April data collection periods had little wind compared with other times of the year. We observed a maximum wind speed of about 5.5 miles per hour. Greater wind speeds may have a larger or non-linear effect on either type of temperature.



Notes: ***: p-value < 0.001; **: p-value < 0.01; *: p-value

Figure 11 Temperature differences (°F) for ambient air temperature and wet bulb globe temperature by segment and site (a) without and (b) with temporal lags

Effect of PlusTi Treatment (Before and After)

After controlling for the temporal, weather, and location-specific characteristics described above, our primary variable of interest is the difference in temperature after the PlusTi cool pavement treatment was installed. Without the temporal lags, we estimated a statistically significant increase in TA by roughly 0.5°F and an increase in WBGT by 0.3°F after the installation of the cool pavement treatment. However, once we control for the autocorrelation using the lags, we estimate a decrease in TA observed by 0.3°F and no statistical difference measured in WBGT. For comparison, shade was estimated to have a roughly similar impact on TA (controlling for lags), but shade also decreased the WBGT sightly as well.

More work is needed to consider the impacts of cool pavement measured at the sidewalk where pedestrians are most active. This will require additional spatial controls that capture the relative differences between the centerline to the sidewalk, from one segment to another.

5.3 UVA/UVB (EXPLORATORY)

As expected, both the UV Index and UVB observations when measuring the radiation from the sky increase in the morning and decrease after solar noon has passed. The UV Index is already at a value of 6.2-6.5 at 11:00 AM, a reading that is considered "high" according to the UV Index instrument manufacturers. By 1:00 PM, the UV Index peaks in the 7.7-8.1 range which is considered "very high" or a level dangerous for human exposure. By 2:00 PM, as the sun recedes the UV Index quickly drops back to the 6.1-6.5 range.

When pointing the UV Index instrument towards the ground, UV reflection levels from the sidewalk—lighter-colored concrete—were generally higher than asphalt treated with PlusTi asphalt rejuvenator: 0.4 on average between 11:00 AM and 2:00 PM compared with 0.2 for the centerline asphalt. However, the exploratory observation suggests that reflection off this treatment is likely a small and negligible part of UV exposure in the pedestrian right of way (~4% UV Index reflected up, on average, compared with the UV Index radiated from the sky).

For UVB Radiation, we observed between 0.22 and 0.26 mW/cm^2 from 11:00AM to 2:00 PM, with no discernable difference when measuring UVB radiation from the sky at the roadway centerline compared with the sidewalk. When measuring the UVB radiating from the ground, we observed no more than 0.01 mW/cm^2 from any location. On average, the amount of radiation measured from the ground was roughly 3% of that measured from the sky.

Again, it is important to note that these measurements are experimental observations collected during the study period. We hope that by documenting our work, we might inspire others interested in experimental heat study designs in the field to consider measuring multiple types of radiation in more systematic ways.

6.0 CONCLUSIONS

Cool pavement treatments often function by increasing the radiation reflected from the surface, and few studies have explored the secondary impacts on increasing heat experienced by those passing by. In this study, we developed a before-after, treatment/control data collection measuring heat data along a roadway treated with the PlusTi asphalt rejuvenator. In our natural experiment study design, we focus on measuring TA and WBGT as proxies for human thermal comfort, such as what we might expect pedestrians and cyclists to experience. While we capture and document TS and UV/UVB radiation, the primary focus of our work is controlling for and capturing the impacts of the treatment on TA and WBGT in a natural environment, controlling for wind, location, and temporal impacts. The impacts of cool pavement technologies on the urban heat island effect and on the durability of pavement are both out of scope for this study.

In this study, we developed a before-after and case-control study design for a cool pavement pilot study of PlusTi cool pavement rejuvenator. We collected observations of TA and WBGT at 10-second increments along the centerline and sidewalks of three segments of the treatment roadways as well as comparable control locations. We then regressed TA and WBGT upon the time of day, presence of shade, wind speed, airport ambient temperature, and site location to compare the difference between measurements before-and-after cool pavement treatment installation. While many companies advertising cool pavement treatments focus on surface temperature measurements, both TA and WBGT better approximate the perceived thermal comfort experience at a pedestrian level.

While we found statistically significant autocorrelation, we were able to control for temporal correlation with residuals by introducing one-minute lags—recognizing that the temperature experienced in the minute(s) before an observation is closely related to the temperature experienced in the observation itself. Once autocorrelation is accounted for, we estimate the PlusTi pavement rejuvenator resulted in a decrease in TA by 0.3°F and no statistical difference measured in WBGT. Controlling for influential environmental factors, this degree of decrease in TA may be considered negligible, or at least very challenging to observe as a pedestrian. Although we did not capture a decrease in measured thermal comfort at a human scale, we still see this as a positive outcome. Our framework for measuring human-scale thermal comfort allowed us to determine whether the reflective nature of the treatment may be increasing heat experienced by pedestrians—or in this case, not.

Natural experiments like this study provide numerous benefits in testing the implications for new applications alongside real-world conditions. While controlled lab experiments offer the ability to remove the numerous confounding factors, many of the confounding factors suppressed (such as wind and age of pavement) are present and persistent factors in the built environment. That said, the limitations of a natural experiment like ours are still numerous. While we aimed to capture enough surface temperature information to control for variations in weather and contexts, the noise in microclimates and subtle impacts of weather data collection days rendered once-per-hour observations not enough to speak statistically about the impacts. For our analysis of TA and WBGT, future work will include incorporating those data into the analysis and controlling for the likely spatial autocorrelation from nearby instrumentation.

Lastly, cool pavement products may play a critical role in lessening transportation infrastructure's contribution to the UHI effect. Urban heat decreases our built environment's ability to cool off at night and exacerbates chronic and acute heat risks. The reflective nature of these kinds of technologies implies that the radiation must go somewhere. While our results study suggests the impacts of PlusTi on pedestrians are somewhat negligible (albeit statistically significant) in our experiment, our study design may provide a framework for evaluating other types of cool pavement treatments across other environments. Heat—particularly in the real world outside controlled laboratory settings—is complicated and difficult to measure. Our ability to evaluate the impacts of our decisions on which heat mitigation strategies to pursue will advance our ability to improve our heat resilience in the face of a rapidly warming climate.

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8.0 APPENDICES

APPENDIX A. LITERATURE REVIEW WORKING PAPER

See project page for the working paper draft under review.
https://nitc.trec.pdx.edu/research/project/1483

APPENDIX B. SUMMARY STATISTICS OF KESTREL DATA BY HOUR AND LOCATION

See project page for excel file summarizing kestrel data by hour and location.
https://nitc.trec.pdx.edu/research/project/1483

APPENDIX C. SCRIPT TO PROCESS AND SUMMARIZE KESTREL DATA

See project page for draft scripts in R-programming language, intended to process and summarize Kestrel data output. https://nitc.trec.pdx.edu/research/project/1483