Solar reflective pavements—A policy panacea to heat mitigation?

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Keywords: cool pavement, urban heat island, heat mitigation, pedestrian thermal exposure

Abstract
Cities worldwide are piloting the use of solar reflective coatings on roads to mitigate the Urban Heat Island (UHI). Solar reflective pavement has been praised as simple, low-cost solution with a demonstrated ability to reduce surface temperature. Less well understood is the effect of solar reflective coatings on radiant heat, which influences human thermal exposure and comfort. We present the first biometeorological observations of solar reflective coating to investigate its thermal performance from a pedestrian perspective. Hourly transects were conducted in two Los Angeles neighborhoods with MaRTy, a mobile platform that measures air, surface, and mean radiant temperature. Transects were performed on July 30, 2019, a typical summer day with low wind speeds and maximum air temperature of 31 °C. The surface temperature of coated asphalt concrete was 4 °C to 6 °C lower than that of regular asphalt concrete, but coated surfaces reflected 118 W m−2 more shortwave radiation on average and up to 168 W m−2 more at noon. In the evening, MaRTy observed 20 to 30 W m−2 of added reflected shortwave radiation on sidewalks next to the reflective pavement. Mean radiant temperature over reflective pavement was 4 °C higher during midday. Although air temperature was reduced by 0.5 °C in the afternoon, after-sunset cooling was negligible. Findings illustrate the benefits and disadvantages of reflective pavement with respect to various thermal performance metrics. Cities should weigh the tradeoffs of UHI mitigation, thermal exposure, implementation and maintenance costs, lifecycle, and other competing priorities in the context of space use.

1. Introduction
Urban heat is an invisible environmental hazard with deadly consequences that poses a growing threat to human health (Matthews et al 2017, Howe et al 2019). Exposure to prolonged heat is expected to increase in frequency, duration, and intensity with continued urbanization and climatic change in the absence of effective adaptation measures (Jones et al 2015). In addition to human health concerns, excess heat in urban areas has implications for air pollution (Sarrat et al 2006) and energy use (Santamouris et al 2001), especially at night when the Urban Heat Island (UHI), i.e. increased urban vs. rural near surface air temperature, is most pronounced (Oke 1982). A wide suite of urban heat mitigation strategies have been proposed that generally fall into one of three categories: urban greening (Oliveira et al 2011, Norton et al 2015), climate-sensitive urban form and design (Emmanuel and Fernando 2007, Pearlmutter et al 2007, Middel et al 2014), or change in materials and material properties, e.g. surface reflectivity (albedo) (Rosenfeld et al 1995, Akbari and Matthews 2012, Georgescu et al 2014). This study presents the first field-based assessment of the heat mitigating performance of solar reflective coating applied to streets.

The inverse relationship between albedo and surface temperature is supported by decades of urban climate scholarship (Rosenfeld et al 1995, Sailor 1995, Taha 1997, Akbari et al 2001, Arnfield 2003, Santamouris 2013, 2014, Georgakis et al 2014, Akbari and Kolokotsa 2016). Field studies, lab experiments, and modeling studies that focus on solar reflective coating and proxy materials have confirmed surface
temperature reductions of pavements and roofs via albedo increases (Synnefa et al. 2011, Carnielo and Zinzi 2013, Santamouris 2013, Georgescu et al. 2014, Mohegh et al. 2017). Many authors have called for promotion of solar reflective coatings on pavement in roads, parking lots, and school play yards (Rosenfeld et al. 1998, Akbari and Matthews 2012, Gilbert et al. 2016). To mitigate the UHI, municipalities in the United States have increasingly explored the use of solar reflective coatings (Estrada et al. 2017, Gilbert et al. 2016). For example, New York, NY and Los Angeles, CA passed cool roof ordinances with reflectance and emittance standards for new and retrofitted roofs (City of New York, Mayor’s Office of Sustainability 2019, City of Los Angeles, Mayor’s Office of Sustainability 2019). Solar reflective coatings are also included in long-term planning documents as UHI mitigation strategy, to enhance resilience to extreme heat, adapt to climate change, and achieve co-benefits such as energy savings and public health benefits. However, UHI mitigation, i.e. the reduction of excess ambient temperature in cities compared to rural surroundings, is often confused with lowering surface temperature—yet another measure that describes a multifaceted concept: heat.

Pedestrian thermal exposure is generally conceptualized as mean radiant temperature (\(T_{\text{MRT}}\)), a synthetic parameter that quantifies the radiative load on the human body (VDI 1998). In hot dry environments, \(T_{\text{MRT}}\) is the main driver of human thermal comfort and the most human-relevant heat metric (Middel et al. 2016). While impacts of solar reflective coatings on air or surface temperature have been widely studied (Santamouris 2013, Georgakis et al. 2014, Middel et al. 2015, Qin 2015a, Mohegh et al. 2017), to date, observational studies on radiative temperature are rare, and the radiative effect of reflective surfaces on pedestrians has only been assessed in physical models (Pearlmutter et al. 2006), not complex urban settings.

Solar reflective pavement interventions, or ‘cool streets’, forefront the issue of human outdoor thermal exposure. Some scholars hypothesize improvements (Synnefa et al. 2007); others predict increased thermal stress and glare (Erell et al. 2014, Taleghani et al. 2016, Taleghani and Berardi 2018). Here, we go beyond modeling and simulation. We present the first \(T_{\text{MRT}}\) on-site measurements of solar reflective coating (Guard Top CoolSeal) using a novel mobile biometeorological instrument platform (MaRTy) that measures all meteorological variables relevant to a person’s weather experience to assess the thermal impacts of albedo increase on pedestrians.

2. Methods

2.1. Study sites

The Los Angeles Streets Department (LA Streets) began piloting the use of solar reflective coatings in residential blocks in 2017. This initiative is part of a broader municipal wide effort to reduce the citywide average temperature by 1.7 °C by 2035 (City of Los Angeles, Mayor’s Office of Sustainability 2019). Los Angeles identified ‘cool pavements’ as one strategy to achieve neighborhood cooling, calling for pilot programs and monitoring to inform the city how to maximize cooling. Los Angeles will expand its heat mitigation efforts to six vulnerable communities by 2021, and ten by 2025 using cool roofs, solar reflective coating, and green infrastructure. In addition, LA Streets will coat 250 lane miles of City streets by 2028. The pLAn also calls for air temperature monitoring and cool streets efficacy studies.

Sun Valley and Pacoima are two of the San Fernando Valley residential neighborhoods that received solar reflective coatings in the summer of 2019 (figure 1). The neighborhoods were selected using the Trust for Public Land Smart Cities Tool (Caryn and Blaha 2015) accounting for heat exposure and socio-economic vulnerability. Each neighborhood received 10 to 12 contiguous blocks of Guard Top CoolSeal surfacing (GuardTop 2018). LA Streets reported surface temperature reductions over 10 °C in both neighborhoods in June 2019 (Mcdowell and Lindblad 2019), a hot and dry month with average maximum air temperature of 26 °C and a few days recording highs of over 32 °C.

2.2. Data collection

The thermal performance of solar reflective pavement was monitored during hourly biometeorological transects using the mobile instrument platform MaRTy (Middel and Krayenhoff 2019). MaRTy measures six-directional longwave (\(L\)) and shortwave (\(K\)) radiation flux densities, air temperature (\(T_a\)), surface temperature (\(T_s\)), horizontal wind speed (\(v\)), and relative humidity (\(RH\)) at pedestrian height (1.1 to 1.5 m). Simultaneous transects were conducted in Sun Valley and Pacoima from 11:00 LST (Local Standard Time) to 21:00 LST on July 30, 2019, a typical Los Angeles summer day with low wind speeds (<1.6 ms\(^{-1}\)) and maximum air temperature of 31.0 °C. Each transect took 50 min to complete and included 24 stops per neighborhood (figure 2): four sites on solar reflective pavement, four reference sites on asphalt concrete, and 16 stops on adjacent cement concrete sidewalks that were separated from the road by a 1 m unobstructed decomposed granite and cement concrete setback. The stops were chosen according to the response time of the slowest sensor to minimize the impact of sensor lag on observed thermal performance (Häb et al. 2015). All biometeorological variables were recorded at 2 s intervals.

2.3. Data processing and analysis

Observed six-directional radiation flux densities were transformed into mean radiant temperature (\(T_{\text{MRT}}\)). \(T_{\text{MRT}}\) integrates the total longwave and
shortwave radiation a human body is exposed to into a single temperature value: \( T_{MRT} = \left( \sum_{i=1}^{6} W_i (a_k K_i + a_l L_i) / a \sigma \right)^{0.25} - 273.15 \) [°C], where \( K_i \) and \( L_i \) are shortwave and longwave radiation flux densities in all cardinal directions [Wm\(^{-2}\)], \( a_k \) and \( a_l \) are absorption coefficients for shortwave (0.70) and longwave (0.97) radiation, \( \sigma \) is the Stefan-Boltzmann constant, and \( W_i \) are weighting factors (0.06 for up/down and 0.22 for cardinal directions) to account for the human body’s elongated shape (Middel and Krayenhoff 2019). All biometeorological variables and directional fluxes were time-detrended to the nearest half hour. The albedo of the monitored surfaces was calculated as daytime average ratio of observed reflected and incoming \( K \). For each neighborhood, average hourly differences and standard deviations of \( T_s \), \( T_a \), reflected \( K \), emitted \( L \), and \( T_{MRT} \) between the reflective pavement and regular asphalt concrete sites were calculated to assess multi-metric thermal performance.

3. Results

We observed albedo, hourly surface temperature \( (T_s) \), six-directional radiation flux densities, \( T_{MRT} \), and air temperature \( (T_a) \) of solar reflective pavement, regular asphalt concrete, and adjacent cement
We decomposed observed six-directional flux densities into their directional longwave and shortwave components to assess the impact of different paving on human thermal exposure (table 2). The coated asphalt concrete reflected up to 130 W m^{-2} (Sun Valley) and 168 W m^{-2} (Pacoima) more shortwave radiation than regular asphalt concrete at solar noon (total incoming shortwave radiation: 1125 W m^{-2}). On average, daytime hourly reflected shortwave radiation increased by 118 W m^{-2} and 144 W m^{-2}, respectively. Conversely, the reflective pavement emitted 33 to 47 W m^{-2} less longwave radiation than untreated asphalt concrete between 11:30 LST and 16:00 LST. Due to this net radiation gain, $T_{MRT}$ over reflective pavement was 4.0 °C higher during midday and 2.0 °C higher in the afternoon than $T_{MRT}$ over asphalt concrete. At low sun angles (early evening), we observed an added 20 to 30 W m^{-2} of reflected shortwave radiation on cement concrete sidewalks adjacent to the reflective pavement. Afternoon near ground air temperature was 0.4 °C to 0.5 °C lower over reflective pavement than uncoated asphalt concrete, but cooling was negligible after sunset (0.1 °C to 0.2 °C, which is in the range of sensor accuracy).

### 4. Discussion and conclusions

MaRTy field observations show that high albedo solar reflective coatings on asphalt concrete reduce surface temperatures to cement concrete sidewalk levels, especially in the mid-to-late afternoon hours. Observed mitigative effects confirm previously reported surface temperature reductions. Conversely, coated streets increased $T_{MRT}$ in the early-to-mid afternoon hours, revealing a direct tradeoff between surface temperature reduction and human heat load on solar reflective pavements. Results are in accordance with biometeorological simulations (Erell et al 2014, Taleghani and Berardi 2018) and suggest that cool pavement does not advance municipal goals

| Sun Valley | Surface temperature [°C] | Pacoima | Surface temperature [°C] |
|------------|--------------------------|---------|--------------------------|
| Time       | C | A | CP | CP-A | CP-C | C | A | CP | CP-A | CP-C |
| 11:30      | 42.7 | 48.3 | 43.1 | -5.1 | 0.4 | 43.0 | 48.2 | 43.6 | -4.6 | 0.6 |
| 12:30      | 46.8 | 53.1 | 47.2 | -5.9 | 0.3 | 46.9 | 53.2 | 47.8 | -5.4 | 0.9 |
| 13:30      | 48.5 | 54.8 | 48.9 | -5.9 | 0.4 | 48.7 | 55.9 | 50.2 | -5.8 | 1.5 |
| 14:30      | 49.1 | 55.3 | 49.3 | -6.0 | 0.2 | 48.9 | 55.8 | 50.3 | -5.4 | 1.4 |
| 15:30      | 48.0 | 53.9 | 48.2 | -5.7 | 0.2 | 47.8 | 54.0 | 49.7 | -4.2 | 1.9 |
| 16:30      | 45.7 | 50.9 | 45.7 | -5.3 | 0.0 | 45.8 | 51.0 | 46.2 | -4.7 | 0.9 |
| 17:30      | 42.5 | 46.3 | 42.3 | -3.9 | -0.2 | 45.9 | 51.0 | 46.2 | -4.7 | 0.9 |
| 18:30      | 39.5 | 42.1 | 38.1 | -4.0 | -1.4 | 45.9 | 51.0 | 46.2 | -4.7 | 0.9 |
| 19:30      |  |  |  |  |  |  |  |  |  |  |
| 20:00      | 30.6 | 32.5 | 30.9 | -1.6 | 0.3 | 31.3 | 33.6 | 31.8 | -1.8 | 0.5 |

| Time       | C | A | CP | CP-A | CP-C | C | A | CP | CP-A | CP-C |
|------------|---|---|----|------|------|---|---|----|------|------|
| 11:30      | 27.6 | 27.5 | 27.8 | 0.2 | 0.2 | 28.6 | 28.3 | 28.6 | 0.3 | 0.0 |
| 12:30      | 30.1 | 30.3 | 30.1 | -0.2 | -0.1 | 31.3 | 30.9 | 31.1 | 0.2 | -0.2 |
| 13:30      | 30.9 | 30.9 | 31.0 | 0.1 | 0.0 | 33.0 | 32.6 | 33.0 | 0.4 | 0.0 |
| 14:30      | 30.8 | 30.8 | 30.7 | -0.1 | -0.1 | 32.7 | 32.8 | 32.7 | -0.1 | 0.0 |
| 15:30      | 30.1 | 30.3 | 29.9 | -0.5 | -0.3 | 32.4 | 32.1 | 32.5 | 0.4 | 0.1 |
| 16:30      | 29.4 | 29.7 | 29.2 | -0.5 | -0.2 | 31.2 | 31.3 | 31.2 | -0.1 | 0.0 |
| 17:30      | 28.9 | 28.8 | 28.8 | 0.0 | -0.1 | 28.6 | 28.3 | 28.6 | 0.3 | 0.0 |
| 18:30      | 28.4 | 28.7 | 27.8 | 0.0 | -0.1 | 28.6 | 28.3 | 28.6 | 0.3 | 0.0 |
| 19:30      |  |  |  |  |  |  |  |  |  |  |
| 20:00      | 23.6 | 23.7 | 23.5 | -0.2 | -0.1 | 24.6 | 24.7 | 24.6 | -0.1 | -0.1 |

Table 1. Hourly air and surface temperature observations with MaRTy in Sun Valley (left) and Pacoima (right) between 11:30 LST and 20:00 LST on July 30, 2019. Summary includes observations on cement concrete sidewalks (C), asphalt concrete (A), solar reflective cool pavement (CP), the difference between CP and A, and the difference between CP and C. Observations that were influenced by shadows from buildings and trees were excluded (blank cells).
Table 2. Hourly radiation flux observations with MaRTy in Sun Valley (left) and Pacoima (right) between 11:30 LST and 20:00 LST on July 30, 2019. Summary includes observations on cement concrete sidewalks (C), asphalt concrete (A), solar reflective cool pavement (CP), the difference between CP and A, and the difference between CP and C. Observations that were influenced by shadows from buildings and trees were excluded (blank cells).

| Time  | Sun Valley | Pacoima |
|-------|------------|---------|
|       | Emitted longwave radiation [Wm$^{-2}$] | Emitted longwave radiation [Wm$^{-2}$] |
|       | C    | A    | CP   | CP-A | CP-C | C    | A    | CP   | CP-A | CP-C |
| 11:30 | 564.4 | 605.0 | 567.3 | −37.7 | 2.9  | 566.2 | 604.4 | 570.6 | −33.8 | 4.5  |
| 12:30 | 594.5 | 642.4 | 596.8 | −45.6 | 2.3  | 595.0 | 643.3 | 601.7 | −41.5 | 6.8  |
| 13:30 | 607.2 | 656.1 | 610.2 | −45.9 | 3.0  | 608.6 | 665.0 | 619.6 | −45.4 | 10.9 |
| 14:30 | 611.5 | 659.9 | 613.0 | −46.9 | 1.5  | 610.1 | 663.6 | 620.8 | −42.8 | 10.7 |
| 15:30 | 603.0 | 648.9 | 604.6 | −44.3 | 1.6  | 602.1 | 649.2 | 616.0 | −33.2 | 14.0 |
| 16:30 | 586.0 | 625.3 | 585.8 | −39.5 | −0.2 | 583.4 | 625.3 | 590.1 | −35.2 | 6.7  |

| Time  | Reflected shortwave radiation [Wm$^{-2}$] | Reflected shortwave radiation [Wm$^{-2}$] |
|-------|------------------------------------------|------------------------------------------|
|       | C    | A    | CP   | CP-A | CP-C | C    | A    | CP   | CP-A | CP-C |
| 11:30 | 165.3 | 62.6 | 179.4 | 116.8 | 14.1 | 189.2 | 80.6 | 225.8 | 145.2 | 36.6 |
| 12:30 | 174.9 | 65.7 | 195.4 | 129.7 | 20.5 | 197.8 | 79.8 | 248.0 | 168.2 | 50.2 |
| 13:30 | 177.3 | 67.7 | 197.7 | 130.0 | 20.5 | 173.9 | 72.1 | 227.1 | 155.0 | 53.3 |
| 14:30 | 166.2 | 63.2 | 191.4 | 128.2 | 25.2 | 197.8 | 79.8 | 248.0 | 168.2 | 50.2 |
| 15:30 | 153.1 | 60.7 | 174.4 | 113.7 | 20.5 | 148.8 | 64.5 | 206.1 | 145.0 | 57.3 |
| 16:30 | 119.0 | 51.8 | 142.7 | 90.9  | 23.7 | 115.5 | 52.7 | 142.5 | 89.8  | 27.0 |
| 17:30 | 74.2  | 34.7 | 96.5  | 61.8  | 22.3 | 49.2  | 19.6 | 69.1  | 47.5  | 11.7 |
| 18:30 | 37.1  | 17.6 | 50.6  | 31.0  | −0.9 | 0.4   | 4.5  | 4.2   | −0.3  | 0.3  |

| Time  | Mean radiant temperature [°C] | Mean radiant temperature [°C] |
|-------|------------------------------|------------------------------|
|       | C    | A    | CP   | CP-A | CP-C | C    | A    | CP   | CP-A | CP-C |
| 11:30 | 61.4 | 58.8 | 63.0 | 4.2  | 1.5  | 60.5 | 57.2 | 61.4 | 4.2  | 0.9  |
| 12:30 | 61.2 | 58.8 | 63.0 | 4.2  | 1.8  | 60.6 | 57.6 | 61.5 | 4.0  | 0.9  |
| 13:30 | 62.3 | 60.2 | 63.2 | 3.0  | 0.9  | 61.7 | 59.8 | 63.5 | 3.7  | 1.8  |
| 14:30 | 64.7 | 63.2 | 65.4 | 2.2  | 0.6  | 62.2 | 61.7 | 64.5 | 2.8  | 2.3  |
| 15:30 | 63.9 | 62.1 | 64.5 | 2.3  | 0.6  | 65.1 | 64.4 | 67.0 | 2.6  | 1.9  |
| 16:30 | 61.3 | 59.9 | 61.1 | 1.2  | −0.1 | 65.1 | 63.7 | 64.9 | 1.2  | −0.2 |
| 17:30 | 57.0 | 56.8 | 57.0 | 0.2  | 0.0  | 24.4 | 24.9 | 23.8 | −1.0 | −0.6 |
| 18:30 | 53.3 | 55.1 | 52.1 | 0.2  | 0.0  | 24.4 | 24.9 | 23.8 | −1.0 | −0.6 |

To promote outdoor activities and walkability for positive health outcomes. Observations also reveal that pedestrian heat load in the early evening may be slightly higher on sidewalks where people walk if the road is not separated by a vegetated setback as noted by Rosado et al. (2017). Observed air temperature reduction over cool pavement was insignificant compared to predicted decreases from whole-city models (Santamouris 2013). Air temperature differences (0.1–0.2 °C) were the same order of magnitude as the sensor accuracy of the air temperature probe (0.1 °C) and can therefore be considered noise. These results are expected due to the limited extent of the cool pavement intervention. Millstein and Levinson (2018) developed an idealized theoretical framework to estimate how far air would have to flow to register a temperature change and found that air temperature at 1.5 m height would have to flow > 200 m over a cooler surface to register a 0.1 °C reduction.

In combination, these findings imply that highly reflective coating cannot substitute all of the microclimate regulating services of vegetation lost to urban development, especially the shade benefits that reduce pedestrian exposure to heat.

Policies promoting widespread adoption of solar reflective coatings can be characterized as ‘policy panaceas,’ (Ostrom et al. 2007); a class of seemingly simple remedies for major environmental challenges that, when universally applied, frequently fail due to faulty assumptions of similarity in conditions in which a problem occurs. The effectiveness of solar reflective coatings is highly context dependent. Reflective coatings likely perform differently between intervention sites because effectiveness is dependent on the background climate and built environment (Salata et al. 2015, Qin 2015a, 2015b). For example, the surface temperature reduction due to highly reflective coating is expected to be smaller in colder climates and sites...
with more cloud cover. Moreover, albedo has different effects on surface, air, and radiant temperatures, and those effects are moderated by urban design—building shape, sky view factor, street setbacks—at the sub-neighborhood scale (Middel et al. 2014, 2017). Although the scientific community recognizes cool pavement creates trade-offs between surface, air, and radiant temperature across times, locations, and scales, policy response is less nuanced. Planning documents and political narratives sometimes frame the Los Angeles cool pavement pilot program as an approach to mitigate UHIs with the co-benefits of reducing energy consumption and reducing human heat exposure, explicitly prioritizing low income areas of the city (City of Los Angeles, Mayor’s Office of Sustainability 2019). Our findings point to the need for policy documents to make explicit which heat-related goals will be advanced by which cooling interventions and to more comprehensively discuss tradeoffs.

Finally, roofs and streets are used differently by people, so the normative ranking of surface, air, and radiant temperature may differ. For instance, while school playgrounds offer abundant government-owned pavement to target for intervention to reduce urban heat and energy costs, playgrounds are recreational spaces used by a vulnerable group (children) at peak T_{MRT} hours. Considering potential tradeoffs between surface and radiant temperature under such conditions is paramount. Alternatively, targeting pedestrian-free roofs reduces concerns about human thermal exposure, but raises implementation challenges related to fragmented ownership (Cool Roof Toolkit 2012).

Cool street interventions are novel experiments that capitalize on an accessible municipal asset by repositioning streets as a solution to UHI, as opposed to a cause, and provide important opportunities to learn how solar reflective coatings work in practice. Our study provides first field observations of T_{MRT}, and others should follow. Measurements were conducted in full sun-exposed locations over 9 h in two similarly treated sites, but more ‘living laboratory’ experiments are needed to investigate diurnal, seasonal, and inter-annual variability as well as differences related to intervention scale, urban form, climatic contexts, and cool surface coating materials.

This study examined one potential trade-off between land surface temperature and T_{MRT}. Other potential cool pavement tradeoffs to consider include increased reflected UV radiation (Epstein et al. 2017), daytime glare versus nighttime visibility, low upfront installation costs versus maintenance costs as materials degrade, and environmental impact over the material lifecycle (Gilbert et al. 2016, Mohegh et al. 2017).

Solar reflective coatings are not a policy panacea for urban heat problems through which similarity in conditions and context can be assumed. Before implementing solar reflective coatings, municipalities should consider all environmental, social, and economic tradeoffs for long-term viability. They also need to consider when and how people use land to decide which heat metric (air, surface, or radiant temperature) should be prioritized. Extrapolations that solar reflective coatings can migrate from roofs to streets as an equally effective means to address UHI, energy consumption, and human heat exposure simplify complex relationships between the built environment and heat.

Acknowledgments

This study was funded by the University of California Los Angeles Luskin Center for Innovation and supported by the Urban Climate Research Center at Arizona State University. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the sponsoring organizations.

Data availability statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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