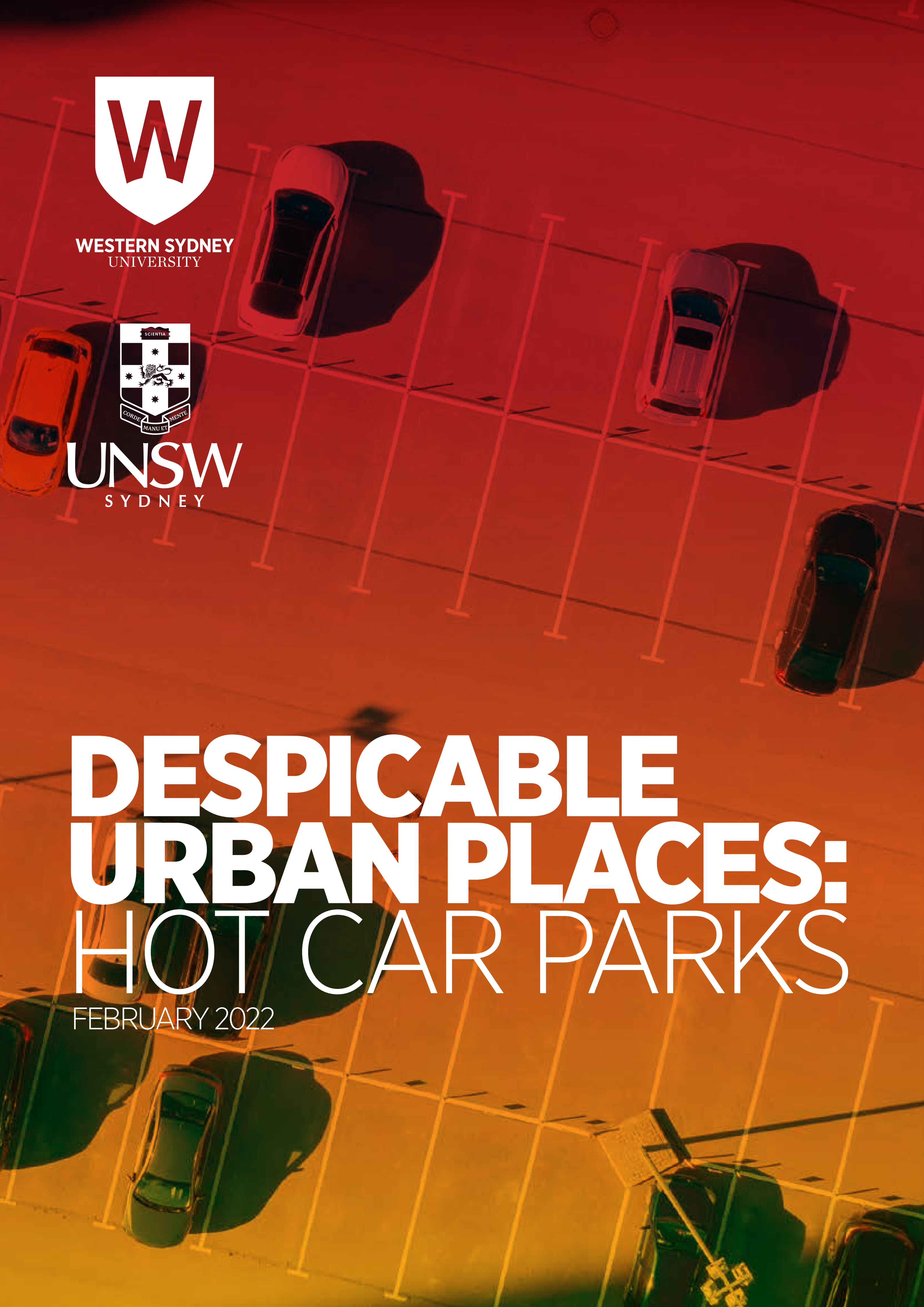

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DESPICABLE URBAN PLACES: HOT CAR PARKS

FEBRUARY 2022

AUTHORS

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Warami! We pay our respect to the Darug people, the traditional custodians of the land on which this work has taken place. For many thousands of years, the Darug have known about the importance of shade. This is indicated by at least three different phrases in their rich language to describe 'shadow' (bawuwan, buwari buwa and gugubuwari). We hope the present work on heat mitigation in car parks will help promote shadow. This will not only increase our capacity to mitigate increasing heat but demonstrate that we do care for people and country.

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> Six square kilometers of at-grade car parks cover western Sydney today. That's 840 soccer fields of nothing but unshaded black asphalt accelerating urban warming. Our research has uncovered that the area of car parks is increasing across the region.
>
> This is not a Sydney-specific issue. It happens in many developed countries. The growing number of unshaded car parks, particularly on the urban fringe, is a symbol of our failure to create communities fit for the 21st century. They reflect an unwillingness to stop out-dated and unsustainable urban sprawl and associated car-dependency.
>
> Worse, these spaces will be with us for decades. In a warming world, improving the design of new and existing car parks is essential. Regulations and guidelines need updating. Shadeless, heat-radiating car parks must become relics of the past. We have the necessary technology. We don't need to wait. We need to change.

DR SEBASTIAN PFAUTSCH
LEAD AUTHOR

QUICK FACTS

Cities are warmer than surrounding non-urban areas. Climate models predict that metropolitan centres will become even warmer due to the dual impacts of global warming and densification. However, the outer fringe zones of metropolitan centres will also become warmer as a consequence of urban expansion that requires replacing green and open spaces like pastures or bushland with grey infrastructure such as roads and buildings.

Limiting the warming effect of urban expansion is possible. It requires dedicated heat-responsive planning and design strategies being applied systematically and at scale. But where should planners and developers start to effectively reduce urban heat?

At-grade car parks are an ideal starting point. They represent the 'low-hanging fruit' for urban cooling efforts. While unavoidable today and in the near future, at-grade car parks are predominately unshaded; made from black, heat-retaining asphalt; widespread and fairly uniform; and often large in size. Changes to current designs of at-grade car parks can therefore have a big impact. A number of strategies to effectively reduce surface heat of car parks are commercially available. Cooling car parks not only addresses their status as local heat islands, but it also leads to lower ambient air temperatures in downwind environments.

This report documents:

- Microclimates across eight car parks and reference sites covered by vegetation.
- Measurements of surface and air temperatures related to a range of car park surface materials.
- The cooling effect of shade in car parks.
- Current design guidelines and policies in Australia related to car parks.
- Alternative design solutions for cooler car parks.

The empirical data and policy analysis are used to develop a set of recommendations for urban heat mitigation that can be applied to new and existing car parks. Because of the common nature of at-grade car parks around the world, the proposed cooling techniques can be applied globally, irrespective of the fact that the underlying case studies and data originated from Sydney.

The most effective cooling techniques for car parks will:

- Reduce the area covered by impermeable black asphalt
- Coat remaining asphalt with reflective surface sealants
- Increase open space (permeable pavements)
- Use solar reflective (light-coloured), porous surface materials
- Use existing tree canopy for shade cover
- Introduce infrastructure for strategic shading
- Use climate-adapted trees species with wide, dense crowns
- Irrigate green infrastructure (active or passive)

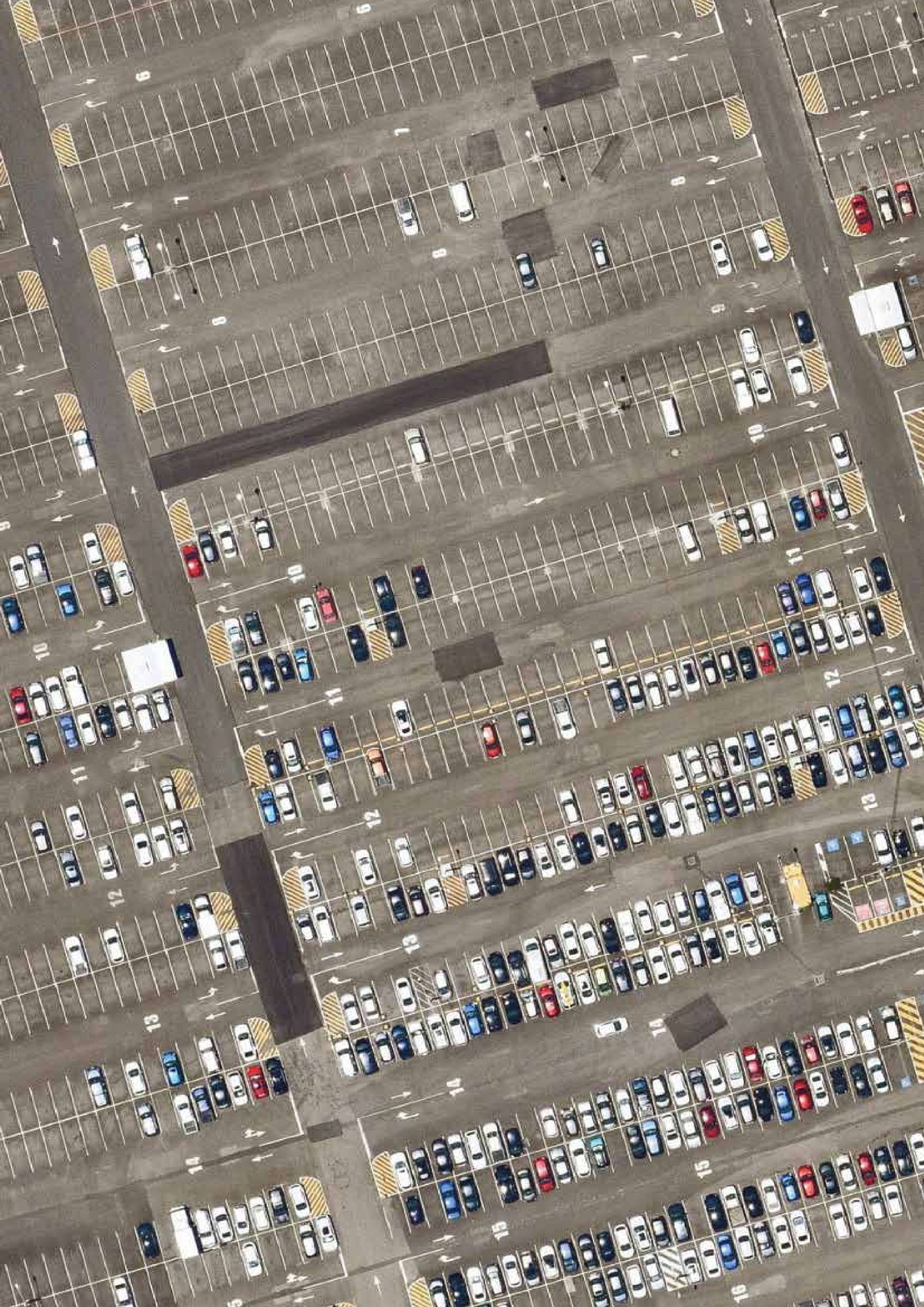
Shade in car parks will also reduce exterior and interior temperatures of parked cars. This effect will lead to reduced emissions as less fuel is required to cool interior air and surface temperatures to safe and comfortable levels.

Further-reaching measures to reduce the impact of car parks on urban microclimates include:

- Using solar panels to shade car parks, with the added benefit of generating renewable energy.
- Green/living facades for multi-level parking lots.
- Infrastructure for active and public transport to limit car-use
- Occupancy surveys to identify optimal car park size and available space for cooling mechanisms
- Transforming unused car parks into green spaces/parks
- Increase smart- and shared-parking options (private and business).

The interrelated impacts of global warming and increasing urban expansion on heat in metropolitan regions, and the positive relationship between growing urban populations and at-grade car parking points towards acceleration of urban warming. This report offers alternatives to avoid this scenario, by transforming car parks from heat islands to cool islands.

CONTENTS



1. THE 'LOW HANGING FRUIT' OF URBAN HEAT MITIGATION

Anthropogenic activities, such as CO_2 emissions, land clearing and urbanisation, are the main driving forces of climate change and its negative impacts, such as global warming directly affecting human health (IPCC 2021). Cities are particularly influenced by global warming because they are already hotter than non-urban environments (Oke et al. 2017). This phenomenon is described as the Urban Heat Island (UHI) effect (Figure 1), which usually is more pronounced at night than during the day (Gago et al. 2013; Oke et al. 2017; Sharifi et al. 2021).

Given the built environment influences air and surface temperatures in cities, we can distinguish two types of UHI effects: atmospheric (UHI_a) and surface (UHI_s) (Oke et al. 2017). The UHI_a effect relates to the air between the ground and the building height, while the UHI_s effect refers to various surfaces' thermal characteristics in urban landscapes (Oke et al. 2017). Typically, the variability of UHI_s effect is more considerable during daytime due to the influence of solar radiation and shade that affect the reflectivity and heat-retention properties of the various materials (Figure 1). The thermal difference between the UHI_a and UHI_s effects is minimised at night because of the lack of solar radiation.

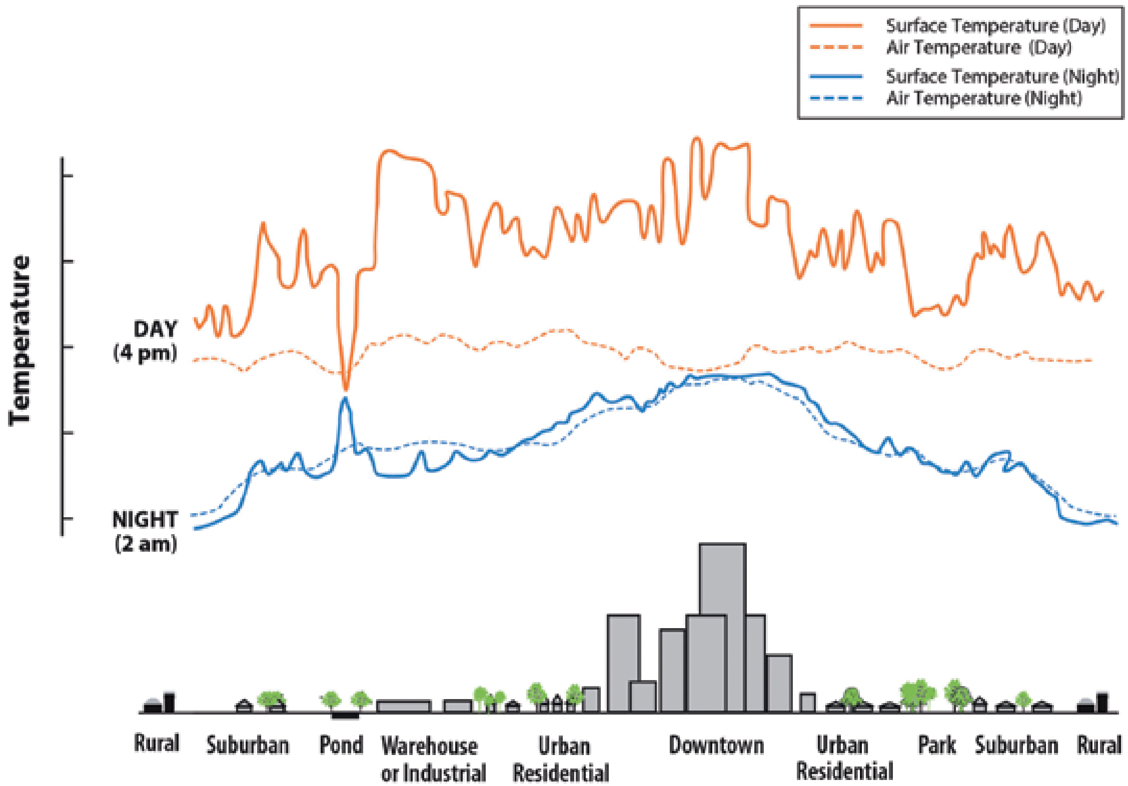


FIGURE 1: The Urban Heat Island (UHI) effect during the day (orange lines) and night (blue lines). The air (dashed lines) and surface (solid lines) temperatures are influenced by various grey, green and blue infrastructures in the urban and the surrounding non-urban landscapes. Surface temperatures are highly variable at daytime due to the influence of solar radiation and shade and the different reflectivity and thermal mass properties of the materials. The lack of solar radiation minimises the differences between the air and surface temperature at night. The densely built city centres are significantly warmer at night due to heat-retaining impervious surfaces, buildings and anthropogenic acitivites, resulting in atmospheric (UHI_a) and surface (UHI_s) urban heat island effects. Image © USGS (2019, https://www.usgs.gov/).

The UHI effect is mainly driven by the continuing replacement of green and open spaces that provide cooling with heat-retaining grey infrastructure, which also increases water runoff (Gago et al. 2013; Oke et al. 2017). At the same time, the tight arrangement of buildings reduces air movement and thus impairs natural cooling in the built environment (Santamouris et al. 2001; Gago et al. 2013). Transport and air conditioning systems generate additional heat that further amplifies the already higher air temperatures in our cities (Santamouris et al. 2001; Oke et al. 2017). While high tree canopy cover could improve local microclimate, trees are often missing, especially in new and densely developed parts of cities and their fringe zones (Gentili et al. 2020; Cheela et al. 2021).

The UHI effect intensifies as we expand and densify cities to meet housing demand (Oke et al. 2017). Currently, more than half of the global population resides in metropolitan areas, and this number is expected to rise substantially by 2050 (Madlener and Sunak 2011; United Nations 2014). Urban residents already experience more days with elevated air temperatures including extreme climatic events like heatwaves (IPCC 2021).

Besides the UHI effect, the phenomenon of urban overheating describes all effects that lead to excess heat in the built environment, intertwining the effects of UHI with advective flows. In coastal cities such as Sydney, the advective heat flows from inland further exacerbate the urban heat island effect generated by the built-up urban cores. In particular, during heatwave conditions, warm winds from inland win over the sea breeze penetration and build a strong synergy with the heat islands, magnifying urban overheating (Khan et al. 2021a, b) .

Not only are extreme maximums during the day very concerning, but so too are the increasing minimum air temperatures for metropolitan areas, indicating a thermal shift of urban climates (IPCC 2021). This is worrying as the gradual warming, and frequent heatwaves increase the risk of heat-related diseases and deaths that can overwhelm emergency services (Luber and McGeehin, 2008). Thus, a change is needed in designing and planning cities by mandating strategies that minimise and alleviate the adverse effects of urban heat (Bowler et al. 2010; Gago et al. 2013; Cheela et al. 2021; Krayenhoff et al. 2021). Widely used approaches for achieving urban cooling include:

- Improved air circulation and avoidance of tight spaces between buildings that trap warm air.
- Retain the existing and introduce additional green and open spaces, including green walls, facades and roofs.
- Introduce blue infrastructure (e.g., creeks, ponds or lakes) where possible to improve daytime cooling.
- Increase the use of high albedo surfaces (i.e., 'cool materials') that reflect rather than store solar energy.
- Preserve mature trees due to considerable potential for reducing surface temperatures through shading and transpirative cooling of ambient air.
- Replace impervious with previous pavements to increase surface evaporation of stored soil water.

A meta-analysis of studies on heat mitigation strategies documented their potential to reduce the ambient temperature by 2-3 °C (Santamouris et al., 2017). These modifications can indeed help alleviate some warming in the built environment and provide much needed mitigation of increasing heat. However, their cooling capacity only unfolds when implemented at scale. It is this requirement for change to more and larger spaces that often limits the effect of the listed modifications on heat reduction. Ownership, spatial and financial limitations, as well as planning policies and design guidelines, can all contribute to this issue.

Among common urban infrastructure elements, at-grade car parks stand out as widespread and large, continuous areas that are regularly deprived of any shade, yet covered in black asphalt. It is well documented that unshaded, conventional at-grade car parks represent local heat islands due to their vast expanse of low albedo, impervious and heat-absorbing surfaces. This report documents the thermal impacts of at-grade car parks on urban microclimate. We see these underdeveloped, paradoxically empty spaces as the 'low-hanging fruit', readily available for effective urban cooling projects. Importantly, we do not exclusively document the bad attributes of these unavoidable hotspots in our cities, but provide a large number of design solutions to improve the thermal performance of urban car parks.

2: THE ROLE OF CAR PARKS IN URBANISATION

Car parks are an omnipresent and typical urban land-use (US EPA 2008; Davis et al. 2010). Depending on the density of the built environment, different types of car parks exist in cities. In compact urbanised areas, parking lots are primarily located underground or established as multi-storey buildings, due to restricted space and competition from other land-uses (Davis et al. 2010). Further, residents in the central parts of the metropolitan areas are less likely to use or even own cars, due to good access to work, shops, friends and family, by either active (walking/cycling) or public transport options.

By contrast, people in the vast swathes of sprawling suburbia are more dependent on cars, with low densities prohibiting active transport options (nothing is within walking distance), and public transport often also under-supplied while car usage is more readily accommodated. In fast-growing urban fringe zones, above-ground, flat ('at-grade') car parks are a standard feature. They are constructed mainly where population growth and urbanisation are on the rise, and land is available and affordable for new development. Worldwide, communities with high car-dependency need parking spaces (Kenworthy and Laube, 1996). This will remain unchanged in future suburbia, so long as land-use patterns and infrastructure continue to accommodate private cars (even electric cars) over shared, active and/or public transport.

Although at-grade car parks seem inevitable and necessary, they take up a large proportion of urban space and are mainly covered with dark-coloured impervious surfaces like asphalt (Akbari et al. 2003; Davis et al. 2010; Hoehne et al. 2020). While most car parks consist of hard surfaces for safe and enduring vehicular use, shade provided naturally by trees or artificially by man-made shade structures is rare (Shoup 2018). Figure 2A shows an example of a typical unshaded asphalt car park adjacent to a large shopping centre in western Sydney (NSW, Australia). The heat from the UHI_s effect can be mitigated by introducing or maintaining natural or artificial shade structures (Erlwein and Pauleit, 2021; Sharifi et al. 2021). Figure 2B provides an example of a parking lot with shading created by trees and a tensile membrane.

FIGURE 2: An example of an unshaded above-ground car park (A) in the suburb of Jamisontown in Penrith Local Government Area (Western Sydney, NSW, Australia). A parking lot with natural and artificial shade in the suburb of Penrith in the same LGA (B). The images were extracted from Nearmap (May 2021).

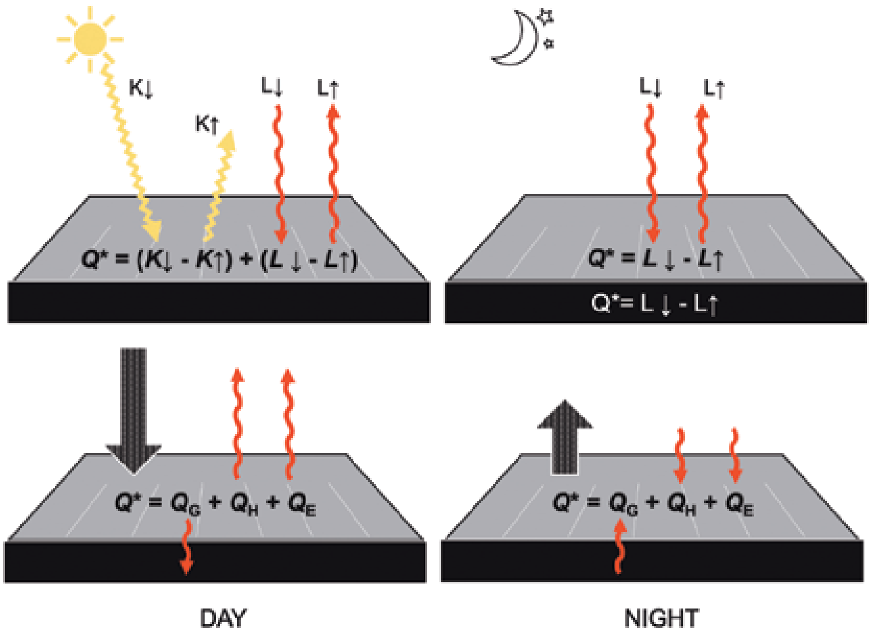


FIGURE 3: The surface energy balance of a conventional unshaded car park during the day and night. During the day (left side), the energy available at the surface (Q*) is the sum of the difference between the fluxes of shortwave (K) and longwave radiation (L). The incoming shortwave radiation ($K_{\downarrow}$) is reflected from the surface ($K_{\uparrow}$), while the incoming longwave radiation ($L_{\downarrow}$) is re-emitted from the surface ($L_{\uparrow}$). The $K_{\downarrow}$- $K_{\uparrow}$ and $L_{\downarrow}$- $L_{\uparrow}$ indicate the portion of the energy that was retained by the material (Q*). The Q* is explained by three heat fluxes: ground (Q_G), sensible (Q_H) and latent heat (Q_E). As the surface warms in the daytime, a small portion of the energy is transferred into the ground (Q_G), and the remaining fluxes heat the air (Q_H) and water (Q_E) in the atmosphere. At night (right side), longwave radiation continues to affect the car park microclimate, with the Q* depending on the difference between $L_{\downarrow}$and $L_{\uparrow}$. The $L_{\downarrow}$ absorbed by the surface during the day is emitted back, with the contribution of longwave radiation from the built environment that also re-emits from the surface. As the surface cools due to radiative cooling with the release of Q_G from the ground, the sensible (Q_H) and latent heat (Q_E) warms car park surfaces. Abbreviations: Q* - energy available at the surface; $K_{\downarrow}$ - incoming shortwave radiation; $K_{\uparrow}$ - reflected shortwave radiation; $L_{\downarrow}$ - incoming longwave radiation; $L_{\uparrow}$ - re-emitted longwave radiation; Q_G - ground heat flux; Q_H - sensible heat flux; Q_E - latent heat flux. Modified from Oke (1987).

In the absence of shade, the open area will receive large amounts of incoming and reflected radiation in the near and far infrared spectrum during daytime (Figure 3). This type of radiation leads to warming of the surface and release of the stored energy in the form of sensible heat (Figure 3; Asaeda et al. 1996; Shoup 2018; Bouzouidja et al. 2021). The energy retained in impervious surfaces like those found in conventional at-grade car parks is released during the day, but importantly long into the night, leading to increased air temperatures (US EPA 2008; Shoup 2018; Hoehne et al. 2020). It follows that unshaded conventional car parks make a measurable contribution to the warming of urban air, which in turn intensifies the UHI_a effect and can reduce human thermal comfort during day and night (Taleghani 2018; Sen et al. 2020).

Unshaded car parks also indirectly lead to higher emissions by cars. In fact, after parking in the sun for hours during a hot day, the indoor air temperature of vehicles can exceed 64°C for black cars, as measured in several experimental settings in California, USA, where sky and thermal conditions are similar to those experienced in Australian summers (Levinson et al., 2011). Such conditions can become life thretening for children and pets inadvertently left in the vehicles even for relatively short periods (Horak et al., 2017). When the driver returns to the car and the air conditioning is turned on at maximum power, it can take up to 20 min to achieve comfortable conditions in the cabin and the emission of NO_x, CO_2 and other pollutants peak, because of the peak power demand of the air conditioning system (Levinson et al., 2011).

Apart from a considerable contribution to local warming of air and reducing human thermal comfort, car parks also enhance water runoff (US EPA 2008; Shoup 2018). The large area covered with impervious materials restricts infiltration of water into the ground, which in turn affects moisture content and cooling in the built environment (Asaeda et al. 1996). As water is redirected into the stormwater system, evaporative cooling from these surfaces is limited to very short periods following summer rain events. Car parks with previous surfaces or engineered solutions to absorb stormwater can generate much greater thermal benefits during times when ambient air temperatures are high.

2.1 URBAN CAR PARKS IN AUSTRALIAN CITIES

If not countered by a substantial shift towards multi-passenger and public transport, the global trend of urbanisation will result in the need for more parking in the future. The highest demand for car parks will occur in fast-growing urban fringe zones, including those around metropolitan areas of Sydney, Melbourne, Brisbane, Perth and Adelaide in Australia.

In Sydney, the increased need for parking primarily applies to the western and southern regions (Greater Sydney Commission 2020). These regions already feature many conventional at-grade car parks where surface temperatures can reach 70°C or more in summer (see this report). At the same time, the availability of green, multi-level or underground car parks that would remain cooler is limited. Given that these areas already experience extreme summer heat (Pfautsch and Rouillard 2019a,b,c; Pfautsch et al. 2020), people are more vulnerable to climate change-driven increases in air temperature. This concerning situation is further exacerbated by the projected doubling in the state's population until 2030 and the associated increase in the use of cars for individual travel (Centre for Population 2021).

After analysing 2250 at-grade car parks covering some 1,300 km^2, across 143 suburbs, a recent study found that asphalt was by far the most common surface material (82% - 96%) in six Local Government Areas (LGA) across western Sydney (Figure 4, Prajapati 2020). While concrete, an alternative surface material with cooler surface temperatures compared to asphalt, was less common (4% -18%; Figure 4, Prajapati 2020). By contrast, permeable surfaces made from gravel , pavers or other porous materials were generally absent (Figure 4). The study also found that tree canopy cover was astonishingly lowin these car parks (~1%, Prajapati 2020). This situation is alarming because black asphalt can reach surface temperatures far above 50°C during clear summer days (Pfautsch and Wujeska-Klause, 2021a). The high thermal mass of asphalt would mean that, if unshaded, Q_G (see Figure 3) would be very high during the day and night, leading to large-scale ambient warming.

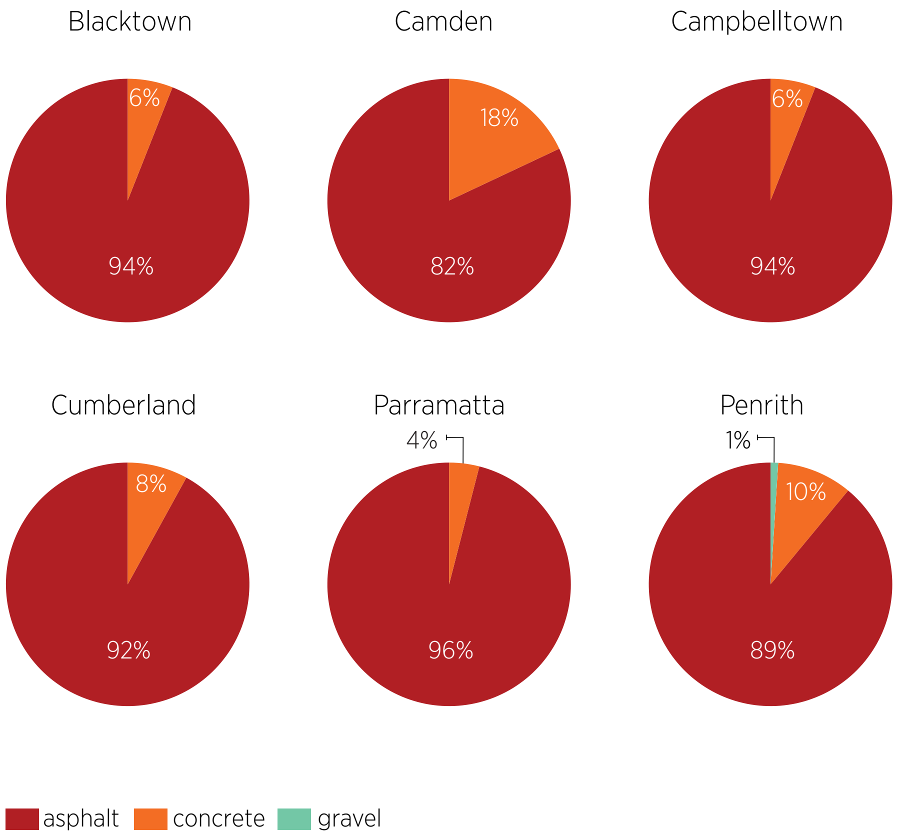


FIGURE 4: A proportion of surface types used for the car parks in six Local Government Areas in Western Sydney. Clearly, asphalt is the most frequently used pavement material (Data used from Prajapati 2020).

The future land transformation from green to grey infrastructure in these sprawling suburbs will amplify the negative impacts of a warming climate. If the thermal influence of car parks is not considered and minimised at the design stage, more at-grade car parks made using heat-retaining materials and limited or no shade will worsen microclimatic conditions and intensify UHI effects (UHI_a, UHI_s) in western and southern Sydney.

3. MEASURING HEAT IN CAR PARKS

How hot do car parks get in summer? To answer this question, the following section provides measurements from three different studies:

3.1 THE SYDNEY ZOO (2018/19)
3.2 HOSPITAL CAR PARKS (2021)
3.3 SYDNEY MARKETS (2019)

All three studies collected continuous and spot measurements of near-surface air (T_{air}), surface ($T_{surface}$) and 'feels-like' (T_{globe}) temperatures. Continuous measurements of T_{air} were collected using either TinyTag loggers (TGP 4500, Gemini Data Loggers, Chichester, United Kingdom) or custom-built temperature loggers designed and manufactured by Western Sydney University.

The TinyTags were covered using Stevenson Shields (ACS-5050, Hastings Dataloggers; Figure 5A), and recorded data continuously every 15 minutes with an accuracy of 0.6°C and resolution of 0.01°C. Each custom-built logger consisted of a water-resistant temperature sensor (Tempmate S1 V2, Imtec Messtechnik, Heilbronn, Germany; Figure 5B) and a reflective aluminium shield protecting the sensor from direct solar radiation. Data were recorded with an accuracy of 0.5°C at 0.1°C increments every 10 minutes. A more detailed description of the construction process, including the comparison with other air temperature sensors and the official network of weather stations from the Bureau of Meteorology (BOM), can be found in Wujeska-Klause and Pfautsch (2020) and Pfautsch et al. (2020).

All spot measurements were collected on sunny, cloudless days. The $T_{surface}$ was measured with hand-held radiometric infrared cameras (FLIR T540 and T640; Figure C and Figure 5D). Aerial spot measurements were taken using a DJI M210 RTK V2 aircraft with a FLIR Zenmuse-XT2 dual-lens camera (Figure 5E). All cameras simultaneously took RGB (red-blue-green) and infrared images. FLIR Tools software was used to extract $T_{surface}$ measurements from the images.

The spot measurements of T_{air} and T_{globe} were collected using a Kestrel 5400 Heat Stress Tracker containing a black globe thermometer that provided a proxi for human thermal comfort (Figure 5F). T_{globe} is a composite measure using air temperature, relative humidity, wind speed, solar radiation and heat re-emitted from ground surfaces. Before measurements were recorded, we allowed the instruments to equilibrate to ambient conditions. After that, T_{air} and T_{globe} were measured 1 m above the ground.

FIGURE 5: Devices used to document air and surface temperatures in the three car park projects. A: TinyTag logger (TGP-4500) for continuous measurements of air temperature; B: Tempmate (S1 V2) logger for continuous measurements of air temperature; FLIR T540 (C), FLIR T840 (D) for ground-based spot measurements of surface temperatures; E: DJI M210 aircraft and FLIR Zenmuse-XT2 camera for periodic aerial measurements of surface temperatures; F: Kestrel 5400 Heat Stress Tracker with black globe thermometer on a tripod.

3.1 ***THE ZOO***

The project took place at Sydney Zoo in Bungarribee, New South Wales, 33 km west of the Sydney CBD. In this study, we assessed the influence of the sun-exposed black asphalt car park on the thermal conditions of the surrounding environment. The impact of the conventional heat-retaining material was compared with a number of more natural surface materials and surrounding environments. The zoo was under construction during the time of the monitoring study.

Measurements of T_{air}, $T_{surface}$ and T_{globe} were collected between 24 October 2018 and 28 March 2019. T_{air} was recorded in four locations, including two car parks, a remnant woodland and an adjacent riparian scrub (location A, Figure 6). Each of the two parking areas were approximately 12,200 m^2. Small trees and sedges had been planted in the vegetation trenches separating rows of parking spaces in the main conventional asphalt car park (location D, Figure 6). At the time of data collection, the vegetation was too short to cast any shade onto the asphalt pavement. The surface of the overflow car park (location B, Figure 6) was made of top soil with sown and emerging grass cover. The remnant woodland (location C, Figure 6) was a protected area of critically endangered Cumberland Plain Woodland, located between the overflow and main car park.

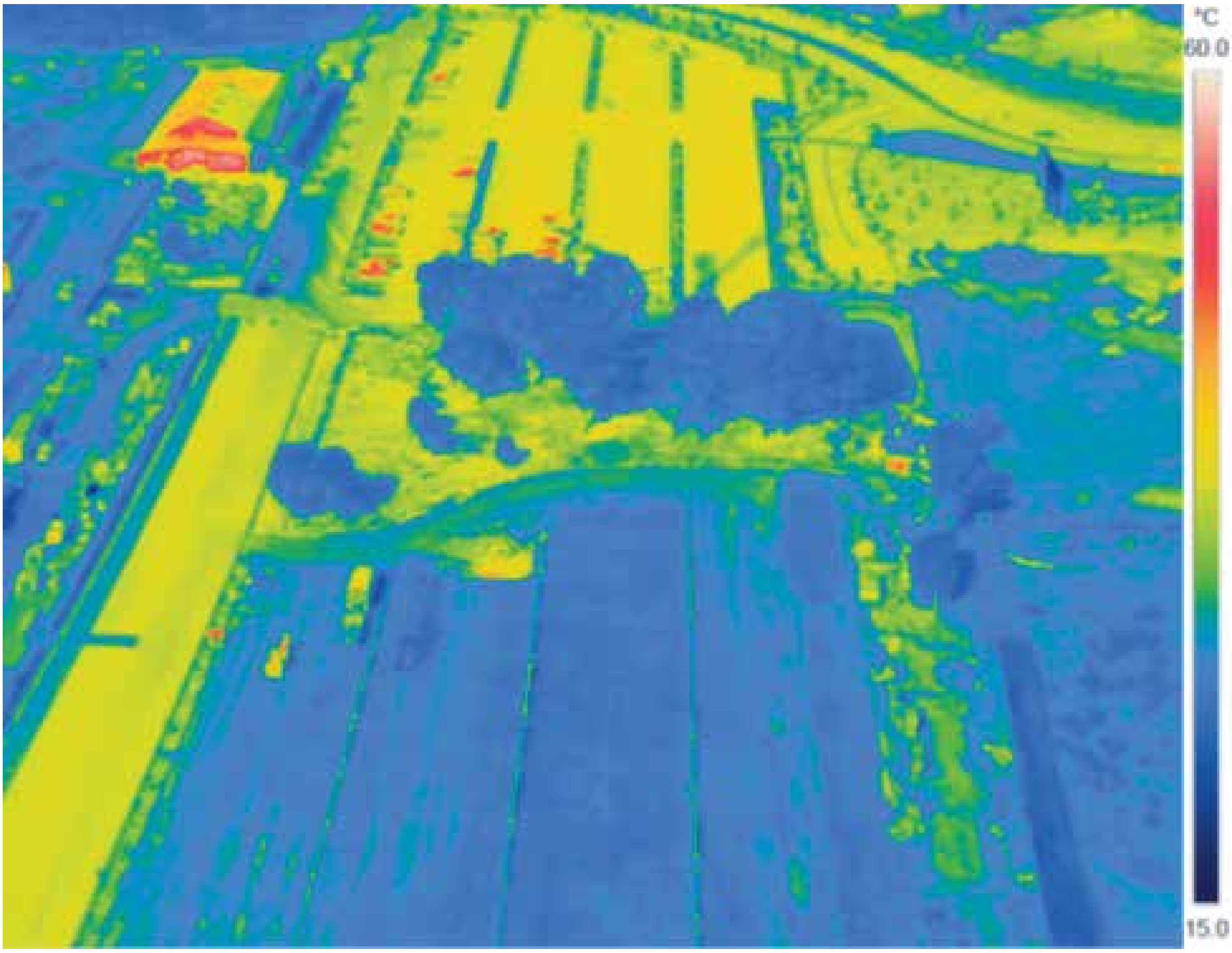
FIGURE 6: Location of four air temperature sensors at the Western Sydney Zoo. The loggers were located in open woodland towards Eastern Creek (A), overflow car park (B), remnant Cumberland Plain Woodland (C) and main parking lot (D). The overview map © Google Earth with the inlet image extracted from Nearmap (April 2019).

We analysed the thermal impact of the two car parks before and after installing the asphalt surface at the main car park, which took place on 9 and 10 February 2019. The measurements collected before 9 February 2019 document baseline conditions, whereas the effect of the sun-exposed asphalt on the surrounding environment was investigated after that date. We investigated how surface temperatures of the two car parks influenced air temperature and human thermal comfort.

SURFACE TEMPERATURE

On 28 March 2019, ambient air temperature during the afternoon reached 26°C (BOM station 67119 – Horsley Park Equestrian Centre AWS – Lat. -33.8510, Long. 150.8567). Figure 7 shows an aerial view of the two car parks measured that day at 16:00. The unshaded asphalt at location D had the highest surface temperature, with a mean of 45°C (± 1.5°C). By contrast, the unshaded grassed surface of the overflow car park (location B) was 17°C cooler than asphalt. This natural surface reached 28°C (± 1.1°C), comparable temperature with the grass measured at location C (2°C difference). These findings show that conventional car park materials warm considerably even on relatively mild days, while vegetated surfaces remain cooler.

FIGURE 7: Infrared image of the grassed overflow car park (location B, foreground) and the asphalt-covered main parking lot (location D, background) at Sydney Zoo. The image was taken at 15:47 on 28 March 2019. The scale on the right side indicates the range of surface temperatures represented by colour. Image © S. Pfautsch



FEELS-LIKE TEMPERATURE

T_{globe} and T_{air} were recorded simultaneously 1 m above ground between 14:00 and 15:00 on 28 March 2019. The instruments measured sun-exposed grass and asphalt surfaces for 15 minutes at 30-second intervals.

Despite the 17°C difference in surface temperatures, T_{air} was comparable for both car parks, being 0.5°C warmer above the asphalt compared to the grass-covered surface (Table 1). While T_{air} was similar, human thermal comfort was much lower on asphalt (+10°C above T_{air}) than on grass (+7°C above T_{air}) (Table 1).

TABLE 1: Air (T_{air}) and feels-like temperatures (T_{globe}) at the main car park (asphalt surface, location D) and overflow car park (grass surface, location B). Values are means (± SD) of N = 32.

	T_{air}	T_{globe}	Δ (T_{globe} - T_{air})
Location B	25.6 (±0.5) °C	33.0 (±2.4) °C	7.4°C
Location D	26.1 (±0.4) °C	36.1 (±2.5) °C	10.0°C

LONG-TERM WARMING OF AMBIENT AIR

T_{air} was recorded continuously between 24 October 2018 and 28 March 2019 using TinyTag loggers. The loggers were housed in a Stephenson Shield, mounted to a star picket 1 m above the ground (Figure 8). A total of 59,752 individual T_{air} measurements were recorded during the 156 days. Temperature derivatives were calculated for data between 1 December 2018 and before 28 March 2019. We assessed thermal conditions across the site and compared the car parks using daytime (10:00 - 18:00) and nighttime (22:00 - 6:00) near-surface air temperatures.

FIGURE 8: Example of positioning TinyTag logger in the open space of the overflow car park (location B) in October 2018. At that time, uncovered subgrade made up the surface of this site and also that of the main car park. Image © S. Pfautsch

Variations in T_{air} showed a general trend among the most natural location A and the most developed location D. For this comparison, T_{air} recorded at each 10-minute time point at location A was subtracted from the T_{air} measurement recorded at the open woodland for the same time point. Results were separated for daytime and night hours.

During the day, the remnant woodland (location A) was on average 1.5°C warmer than the main car park (location D; Figure 9). This mean difference in daytime T_{air} was similar before and after asphalt pavement was installed. Similarly, the absolute daytime differences were comparable (before: 5.5°C; after: 5.7°C). The opposite trend was observed at night, where T_{air} was on average 2.3°C warmer over the main car park compared to the remnant woodland (Figure 9). The thermal conditions at night were less favourable with asphalt (after mean ΔT_{air}: 2.6°C) than previously used compacted sub-surface (before mean ΔT_{air}: 2.0°C) (Figure 9). The absolute nighttime ΔT_{air} reached 6.7°C (before) and 7.5°C (after).

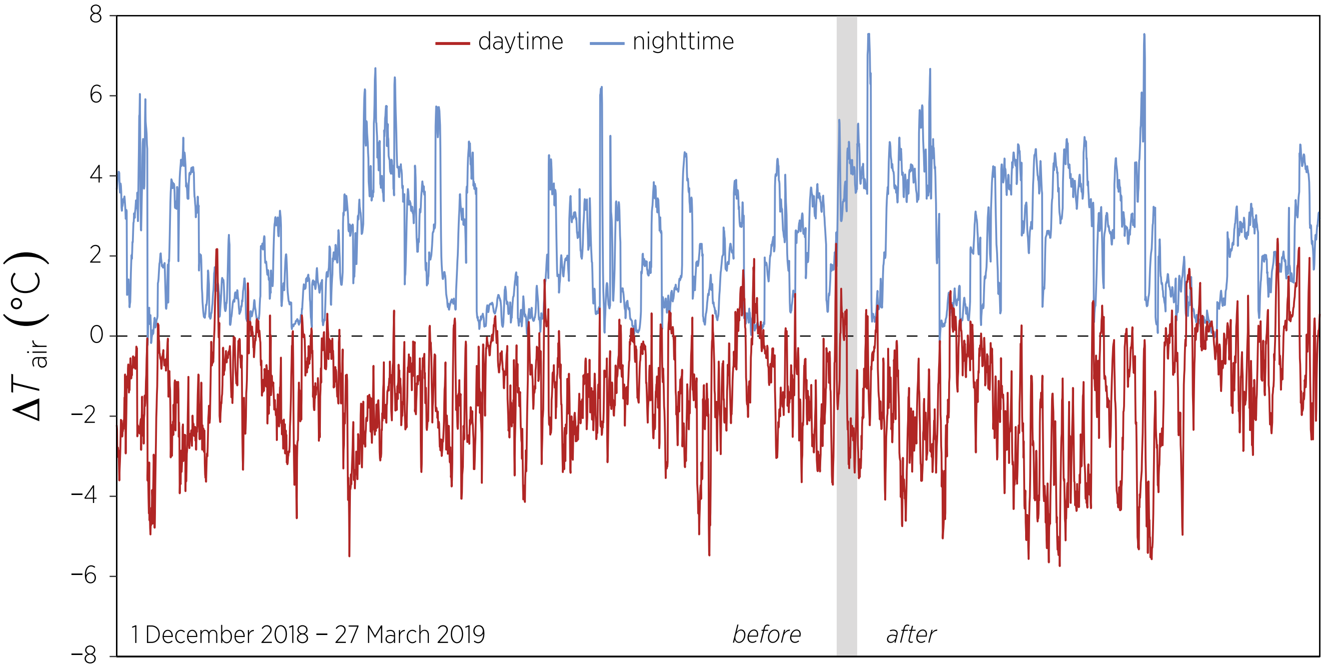


FIGURE 9: Temperature differential (ΔT_{air}) between the main car park (location D) and the open woodland (location A) during daytime (10:00 - 18:00; red line) and nighttime (22:00 - 06:00; blue line). The data presented is based on 10-minute measurement intervals. Negative values indicate that T_{air} at the main car park was lower compared to T_{air} at the open woodland location. Positive values indicate the opposite, indicating a warming effect. The dashed line signifies zero ΔT_{air} where T_{air} at both locations would be in equilibrium. The shaded area indicates when the asphalt was applied to the main car park.

Given the overall thermal trend across the site (Figure 9), the daytime and nighttime conditions of the two car parking areas (locations B and D) were also assessed. The ΔT_{air} was negligible during the day, with only 0.1°C warmer air over the natural (location B) compared to the man-made surface (location D) (Figure 10). The largest absolute daytime ΔT_{air} were 1.7°C (before) and 2.1°C (after). By contrast, air above the main parking lot was on average 0.8°C warmer at night compared to the overflow car park (location B) (Figure 10). The nighttime thermal conditions were generally warmer after the asphalt was laid (after ΔT_{air}: 1.1°C) compared to compacted subgrade at both locations (before ΔT_{air}: 0.6°C) (Figure 10). The absolute nighttime ΔT_{air} reached 3.5°C (before) and 4.2°C (after).

When hot summer days reached 40°C (27 - 31 December 2018), the nighttime air temperature was cooler at location B than the main parking lot, with the difference varying from -1.7°C to -0.7°C. Interestingly, the thermal differences between the locations were more significant during slightly cooler days (T_{air} > 35°C) after the asphalt was applied and the grass grew (17 and 18 February 2019). The daytime T_{air} was on average 0.5°C - 0.6°C warmer on the grass (location B) than the asphalt (location D), but it was 1.8°C - 2.1°C cooler at night.

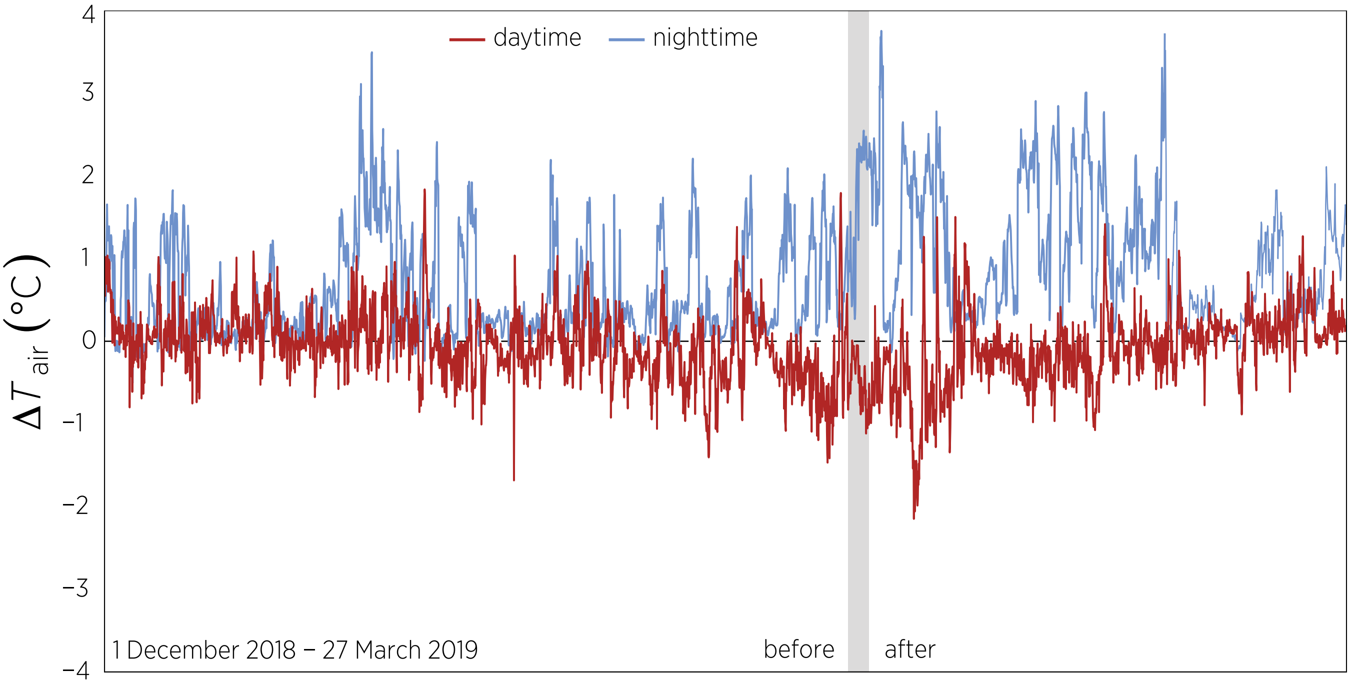


FIGURE 10: Temperature differential (ΔT_{air}) between the main asphalt (location D) and overflow grass car park (location B) during daytime (10:00 - 18:00; red line) and nighttime (22:00 - 06:00; blue line). Negative values indicate that T_{air} at the asphalt was lower compared to T_{air} at the grass car park. Positive values indicate the opposite, indicating a warming effect. The dashed line signifies zero ΔT_{air} where T_{air} at both locations would be in equilibrium, while the shaded area indicates when the asphalt was applied to the main car park.

Findings from the *Zoo project* clearly show that heat-retaining car park surfaces like black asphalt can warm considerably even on a mild day. The solar energy absorbed by the main car park lowered human thermal comfort during the day. Most striking is the clear warming effect on air temperatures during the night by the unshaded asphalt car park.

3.2 ***HOSPITAL CAR PARKS***

The project took place at Liverpool Hospital, around 25 km southwest of Sydney's CBD (Figure 11). In this project, we compared the thermal properties of three surface materials used in car parks (Figure 11) - black asphalt (locations A and F), brick pavers (location B) and concrete (locations D and E). A grassed area in the middle of the study site (location C) was used as 'cool' reference material. An essential aspect of this study was to define the cooling effect of trees and shade cast by buildings on surface temperatures.

FIGURE 11: Location of the car parks at the Hospital in Liverpool Local Government Area (LGA). The sequence of car parks refers to the order of measurements. A: main asphalt car park; B: brick car park; C: grass reference area; D: concrete car park near childcare centre; E: a multi-storey concrete parking lot; F: overflow asphalt car park. The overview map © Google Earth with the inlet image extracted from Nearmap (January 2021).

Recordings were made for $T_{surface}$, T_{air} and T_{globe}, as well as for incoming and reflected radiation to calculate surface albedo. The equipment used for the measurements is shown in Figure 12. The measurements were collected on 24 January, 5 February and 2 April 2021. New concrete on the top deck of the multi-storey car park was not measured on 24 January due to increased cloud cover in the afternoon. The days differed in the ambient thermal conditions as indicated by the daily maximum T_{air} measured at the nearest BOM station (Station 66137 – Bankstown Airport AWS – Lat. -33.9176, Long. 150.9837). Based on the maximum ambient temperature, the days were classified as mild (27.1°C, 2 April), warm (29.7°C, 5 February) and hot (38.5°C, 24 January). Given the contrasting ambient thermal conditions on these days, the results are discussed separately for each condition.

Solar radiation measurements were conducted with a double-pyranometer (i.e., two back-to-back solar radiometers, part of a NR01 by Hukseflux, Figure 12A) in the sun and the shade, measuring incoming and reflected shortwave radiation (measuring between 285 and 2,800 nm). Further, the same instrument – a 4-component net-radiometer - was equipped with a double pyrgeometer, measuring incoming and outgoing thermal radiation (measuring between 4,500 and 40,000 nm). The data was recorded in clear sky conditions at 0.4 m above the ground for 5 minutes at 15-second intervals between 11:30 and 16:00, depending on the day. In total, 560 individual measurements were recorded for each parameter across the three days. This project reported albedo, which represents the effectiveness of the surface in reflecting incoming solar radiation, namely the ratio of reflected to incident sunlight. The values close to 0 indicate materials that reflect little and absorb most solar energy, which then increases the surface temperature and is dissipated as heat by convection. By contrast, values approaching 1 refer to materials that reflect most of the incoming solar radiation, and thus store very little energy contained in solar radiation. Further, the net radiation Q* (expressed in W m^{-2}) was computed considering the all-wavelength radiative balance as:

$$Q^* = K_{\downarrow} - K_{\uparrow} + L_{\downarrow} - L_{\uparrow}$$

Where, following the notation used by Oke (1987), $K_{\downarrow}$ is the downwelling (incoming) shortwave (solar) radiation, $K_{\uparrow}$ is the upwelling (reflected) shortwave radiation (incoming radiation times the albedo of the surface), $L_{\downarrow}$ is the incoming longwave (i.e., infrared) radiation from the sky, and $L_{\uparrow}$ is the upwelling radiation, namely the thermal radiation reflected and emitted by the urban surface (following the Stefan-Boltzmann equation).

Net radiation offers an appraisal of how much energy enters or leaves a system. When $Q^* > 0$, the system (e.g., a pavement or the entire city) is gaining energy, while when $Q^* < 0$ a system is radiatively cooling. Excluding the contribution of anthropogenic heat, the net radiation describes the energy that drives evaporation and sensible heat fluxes (Offerle et al., 2003).

$T_{surface}$ of the pavements and grass was measured in the sun and shade between 13:00 and 16:30. The data were recorded at five locations (A - E). During the three days, 194 ground-based images were taken at these sites. In the end, 20 images were used to extract five random spot measurements for each target surface, light condition and day, resulting in a total of 140 $T_{surface}$ data points.

The 'feels-like' (T_{globe}) and air temperature (T_{air}) were measured 1 m above the target surfaces. They were recorded simultaneously on the same material in the sun and shade with two Kestrel Heat Trackers (Figure 5F). On each surface type, the data were measured for 10 minutes at 30-second intervals between 12:30 and 16:30, depending on the day. In total, 560 individual measurements were collected over sunlit and shaded surfaces. Moreover, air temperature and wind speed were also measured at 1.1 m and 0.30 m, with two identical weather stations (MetPak-Pro by Gill Instruments) mounted on the same cart of the net-radiometer (Figure 12A).

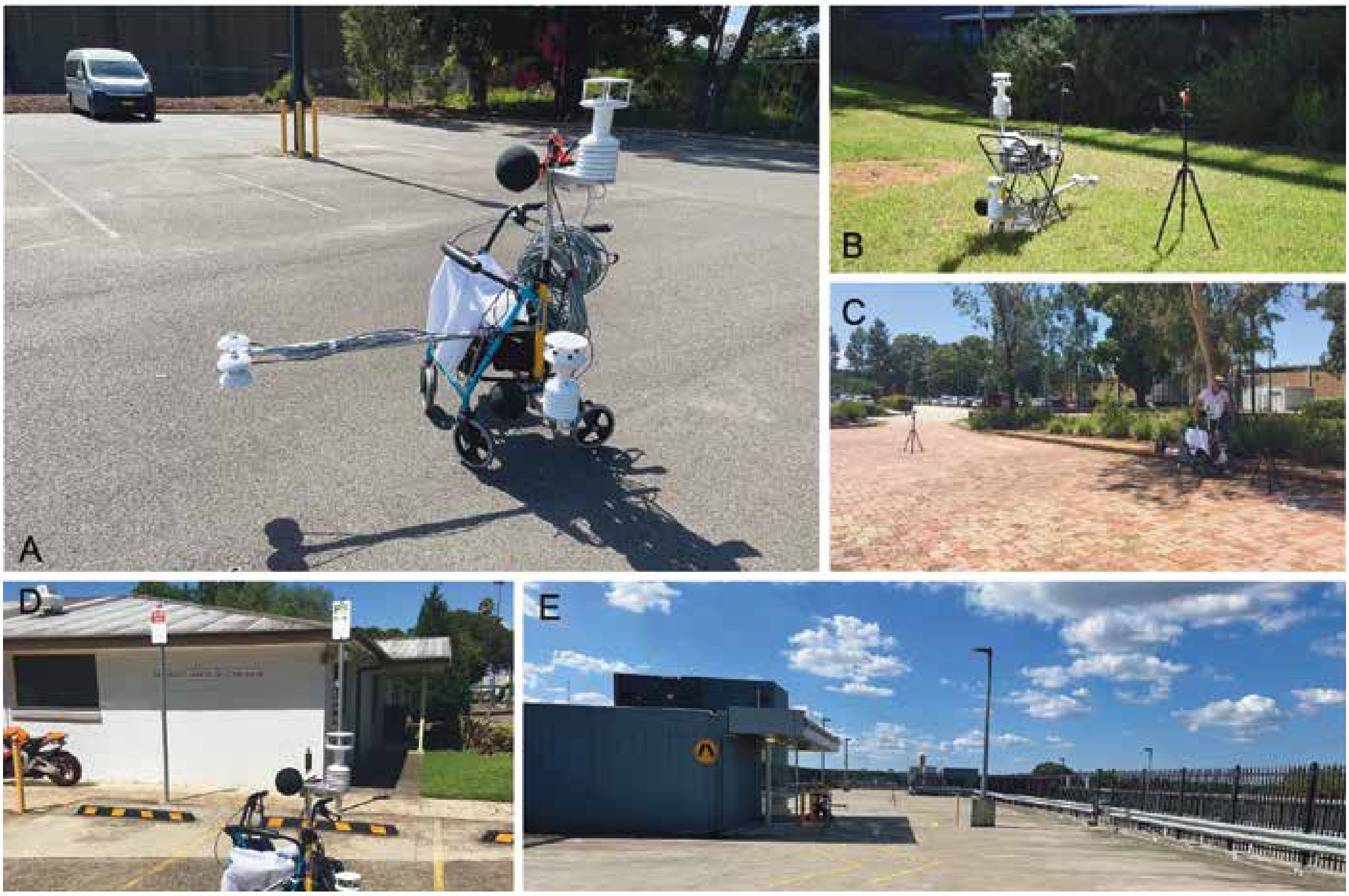


FIGURE 12: Examples of solar radiation and 'feels-like' temperature measurements taken at the car parks and the reference grassed area at the Liverpool Hospital. A: main asphalt car park; B: grass reference area; C: brick car park; D: car park near childcare centre (old concrete); E: top level of the multi-storey car park (new concrete). Images © S. Pfautsch

In addition to measurements during the three individual days, T_{air} was recorded continuously between 25 January and 18 March 2021 using three custom-made air temperature loggers. They were positioned 2.5-3.5 m above the ground on tree branches at locations A and B, including a light pole at location E. Figure 13 depicts a custom-made logger on the tree branch above the brick car park at location B. A total of 22,896 individual T_{air} measurements were collected during the 53 days. Various temperature derivatives were calculated during the study period and analyzed for the different car parks.

FIGURE 13: Example of positioning the custom-made logger to the tree branch at the brick car park (location B). Image © S. Pfautsch

MILD DAY

On 2 April 2021, the ambient air temperature reached a maximum of 27.1°C (BOM). On that mild day, the surface albedo of the car parks ranged between 0.10 and 0.27 (Table 2). The lowest value of 0.10 was recorded for asphalt at location A. This pavement type absorbed a significant proportion of incoming solar radiation (Table 2) and had the highest relative net-radiative balance. Pavement materials with lighter colours had a higher albedo (0.17 - 0.22) and absorbed less energy than asphalt (Table 2). New concrete at the top deck of the parking lot (location E) had the highest surface albedo of 0.27 (Table 2).

TABLE 2: Albedo measured at the car park and grass surfaces in the sun on a mild day (2 April 2021). A value for each surface represents a mean (±SD) of 20 individual measurements. The relative net radiative balance (%) was calculated as 100% minus the ratio of outgoing to incoming radiation (shortwave and longwave) and describes how much radiation enters the pavement system. The old and new concrete surfaces were measured at the childcare centre (location D) and the top-level of the multi-storey car park (location E).

Measurement type	asphalt (location A)	brick pavers (location B)	old concrete (location D)	new concrete (location E)	grass (location C)
Surface albedo	0.10 ± 0.00	0.21 ± 0.01	0.17 ± 0.00	0.27 ± 0.01	0.22 ± 0.03
Net radiation (Q*, W m^{-2})	529	544	452	370	479
Relative net radiative balance	46%	44%	44%	33%	42%

In the sun, $T_{surface}$ ranged from 31°C (grass) to 41°C (new concrete; Figure 14). Black unshaded asphalt warmed to 36°C. When shaded, pavements were up to 14°C cooler, reaching values <28°C. The most considerable temperature reduction was found for black asphalt (location A: -38%) and old concrete (location D: -40%), the least was detected between sunlit and shaded grass. Figure 15 shows examples of sunlit and shaded car parks measured on a mild day.

T_{air} and T_{globe} were comparable among sunlit surfaces, though T_{globe} was more than 10°C warmer compared to T_{air} (Figure 14). Similar to $T_{surface}$, shade significantly reduced T_{globe} yet had a much lower cooling effect on T_{air}. Although the thermal conditions were mild on 2 April 2021, the findings indicate that pavement characteristics play an important role in surface heat and human thermal comfort even during sunny days where ambient air temperatures are pleasant.

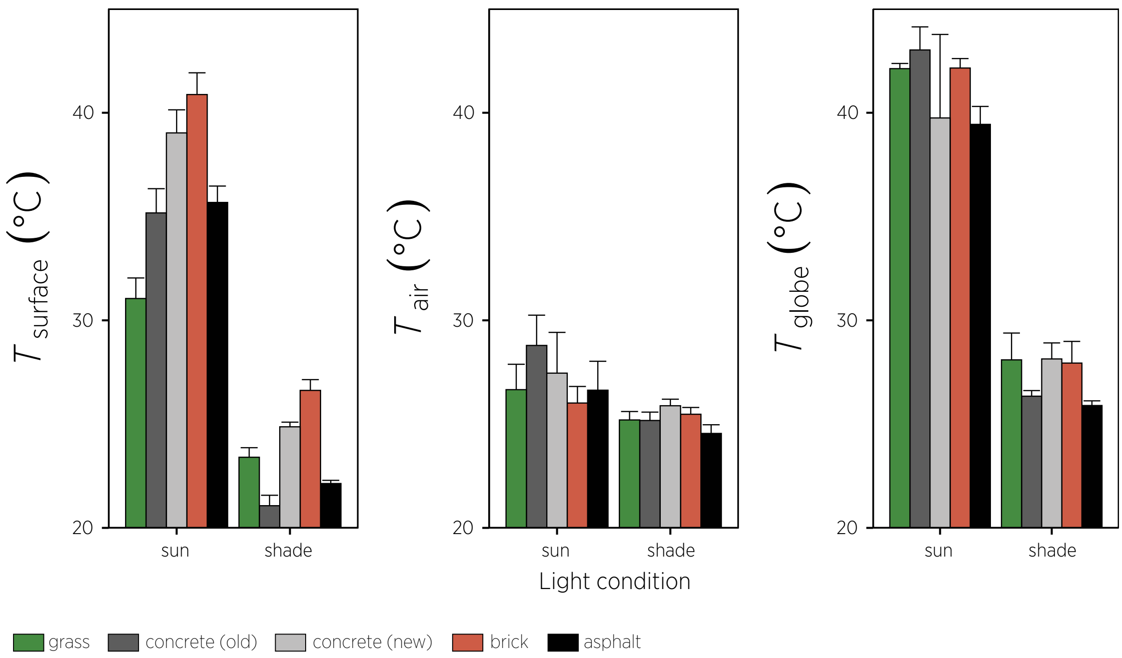


FIGURE 14: Surface ($T_{surface}$), air (T_{air}) and 'feels-like' (T_{globe}) temperatures of the asphalt, brick, two types of concrete, and grass measured on a mild day (2 April 2021) at Liverpool Hospital. The concrete surfaces were measured at the top of the multi-storey car park (new) and near a childcare centre (old). The measurements were collected in the sun and shade. The bars represent a mean of $N = 5$ ($T_{surface}$) or $N = 20$ (T_{air}, T_{globe}) and the error bars indicate one standard deviation.

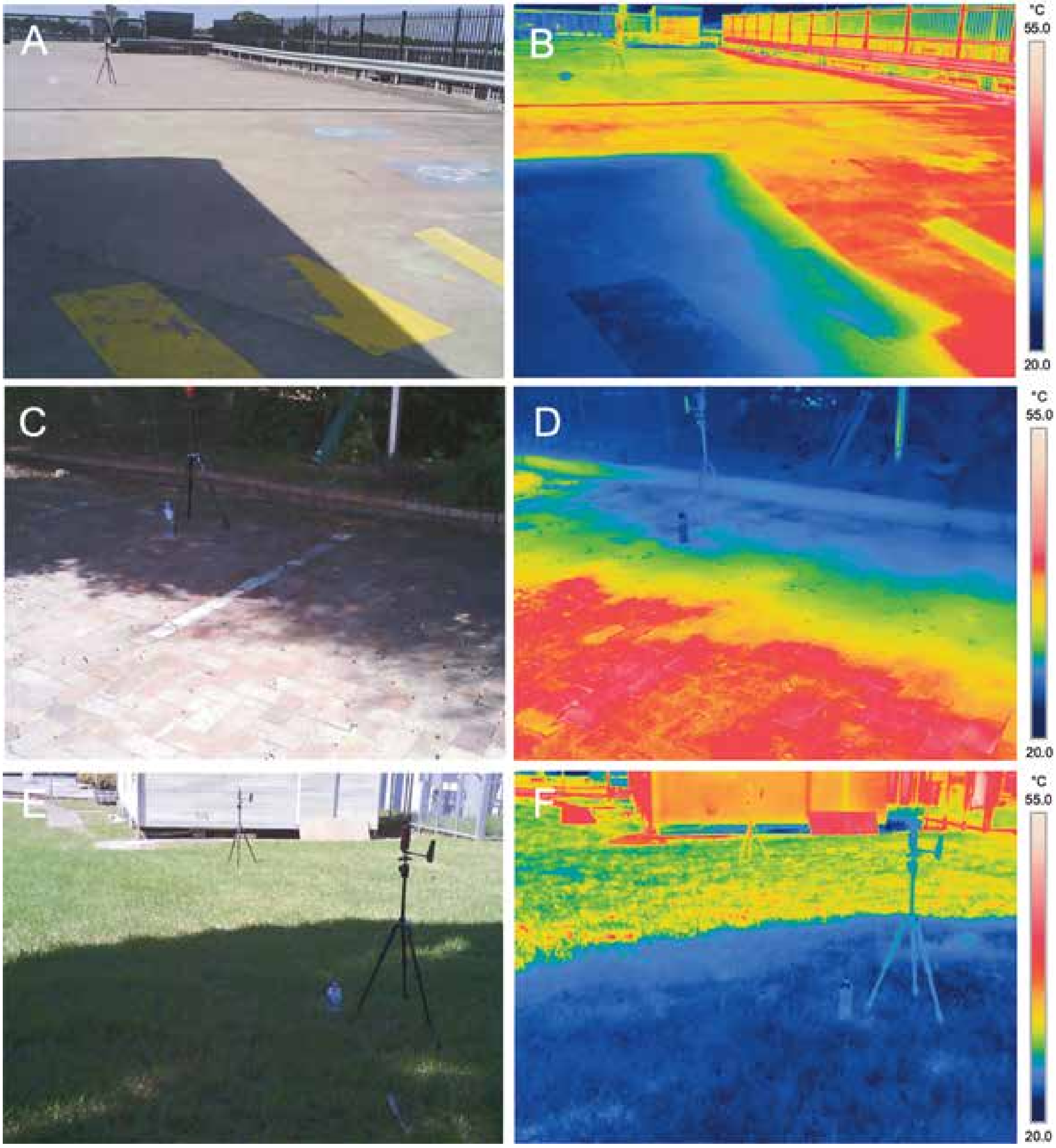


FIGURE 15: Normal (a, c, e) and infrared (b, d, f) images of pavement surfaces at location D (a, b), B (c, d) and C (e, f). The infrared images on the right show the surface temperatures captured for the different types of materials in the sun and in the shade. The images were taken at 14:52 (a, b), 13:28 (c, d) and 13:57 on 2 April 2021. The scale on the right side indicates the range of surface temperatures represented by colour. *a-b*: The surface temperature of the sunlit concrete at the top level of the multi-storey car park was on average 39°C, 14°C warmer than in the shade. *c-d*: sunlit brick car park reached a mean surface temperature of 41°C, 14°C warmer than in the shade. *e-f*: sunlit grass reached a mean surface temperature of 31°C, 8°C warmer than in the shade. Image © S. Pfautsch

WARM DAY

The ambient temperature reached 29.7°C (BOM) on 5 February 2021, 2.6°C hotter than on a mild day (2 April 2019). Light conditions were slightly different during this day being 2 months earlier in summer compared to those present during the mild day. However, the overall grouping of materials and their range of albedo remained similar (Table 3). Most variable was albedo of grass, which decreased from 0.22 to 0.18 (Table 3). That variability was likely associated with pigments and the physiological characteristics of harvesting sunlight by plants.

TABLE 3: Albedo measured at the car park and grass surfaces in the sun on a warm day (5 February 2021). The description of measurements is identical with Table 2.

Measurement type	**asphalt** (location A)	**brick pavers** (location B)	**old concrete** (location D)	**new concrete** (location E)	**grass** (location C)
Surface albedo	0.10 ± 0.00	0.18 ± 0.00	0.17 ± 0.00	0.29 ± 0.00	0.18 ± 0.00
Net radiation (Q*, W m^{-2})	691	670	498	424	722
Relative radiative balance	48%	46%	43%	34%	51%

The $T_{surface}$ of all sunlit car parks increased with warming and ranged from 34°C to 58°C (Figure 16). Compared with a mild day, the most significant heating was found for asphalt (location A: 58°C), bricks (location B: 49°C) and concrete (location D and E: 46°C). By contrast, the most negligible rise in $T_{surface}$ was observed for the grass at location C (34°C), making its $T_{surface}$ 24°C cooler than that of asphalt.

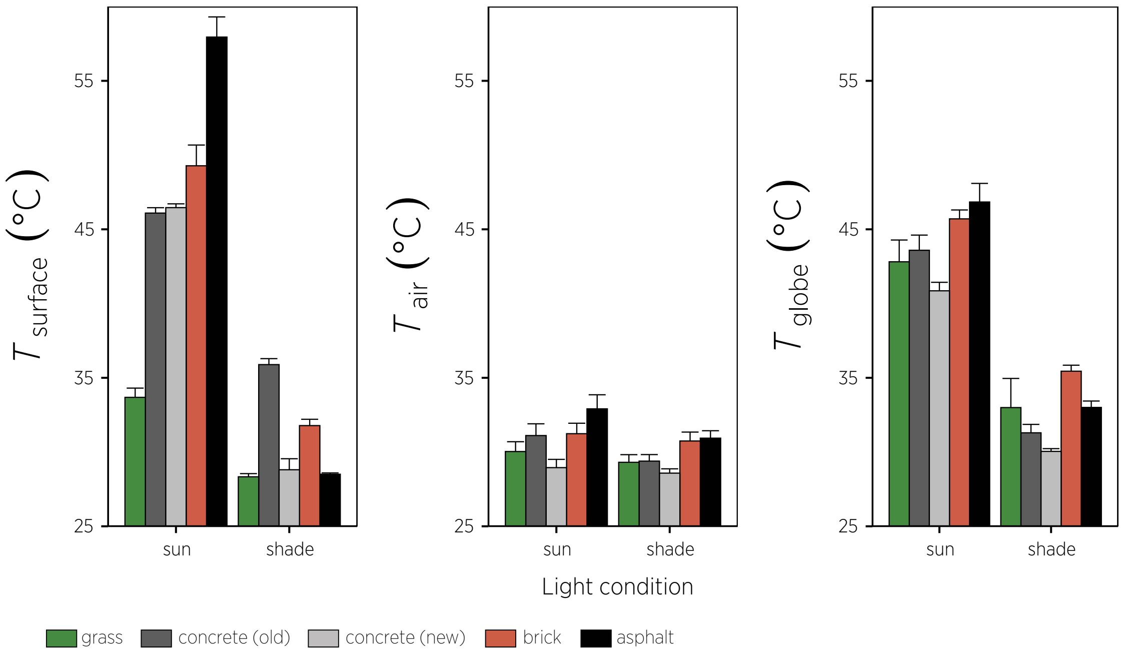


FIGURE 16: Surface ($T_{surface}$), air (T_{air}) and 'feels-like' (T_{globe}) temperature of the asphalt, brick, two types of concrete, and grass measured on a warm day (5 February 2021) at the Liverpool Hospital. The description of elements in a plot is identical with those described for Figure 14.

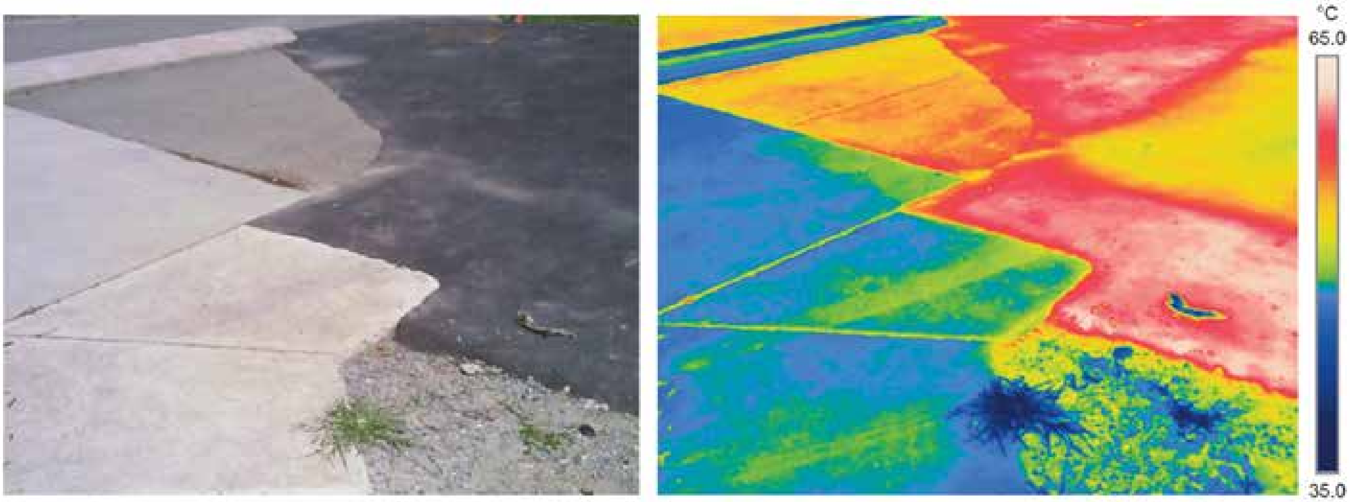


Figure 17 depicts surface temperatures of old and new concrete and asphalt. In the mid-afternoon, the new asphalt was the hottest surface with a mean $T_{surface}$ of 62°C (right side), 6°C warmer than the aged pavement of the same material (top left). By contrast, the concrete pavement had a markedly cooler surface temperature. This comparison highlights that not only different materials, but also the age of individual pavements play an important role in the thermal characteristics of car parks.

FIGURE 17: Normal and infrared image comparing the surface temperature of old and new concrete and asphalt pavement types. The image was taken at 14:34 on 5 February 2021. The scale on the right side indicates the range of surface temperatures represented by colour. The surface temperature of concrete (mid and bottom left) was on average 49°C. The new asphalt (right) had a mean surface temperature of 62°C which was 6°C warmer than the old asphalt (top left). Image © S. Pfautsch

The effect of shade on $T_{surface}$ was even greater on this warm day compared to the mild day. Shade reduced $T_{surface}$ of asphalt from more than 60°C to below 30°C, or more than 50%. The reduction of $T_{surface}$ of the other surface types were similar to those recorded during the mild day. T_{air} ranged from 29°C to 33°C in the sun, while T_{globe} was between 41°C and 47°C (Figure 16). The air above asphalt (location A) was the warmest (33°C), which also felt the hottest that day (T_{globe}: 47°C; Figure 16). Shade significantly reduced the T_{air} and T_{globe}, the magnitude of this reduction was, however, considerably smaller than on the mild day.

HOT DAY

On a hot day (24 January 2021), the maximum ambient air temperature was 38.5°C (BOM). This was one of the hottest days in this project. Like other measurement days, black asphalt at location A had the lowest albedo and thus the smallest portion of solar energy reflected (Table 4). Grass reflected most of the sunlight as indicated by the highest albedo (0.28), resulting in the smallest relative net radiative balance (34%; Table 4).

TABLE 4: Albedo measured at the car park and grass surfaces in the sun on a hot day (24 January 2021). Description of measurements is identical with Table 2. New concrete was not measured on this day.

Measurement type	asphalt (location A)	brick pavers (location B)	old concrete (location D)	grass (location C)
Surface albedo	0.10 ± 0.00	0.21 ± 0.00	0.17 ± 0.00	0.28 ± 0.01
Net radiation (Q^*, W m^{-2})	641	566	411	428
Relative net radiative balance	44%	40%	35%	34%

All car parks were hotter compared to measurements collected during the mild and warm days. $T_{surface}$ ranged from 46°C (grass) to 69°C (asphalt) in the sun (Figure 18). The asphalt at location A had the most considerable rise of $T_{surface}$ (+32°C). Sunlit brick pavers were 9°C (location B: 58°C) and aged concrete 18°C 'cooler' compared to asphalt. Once shaded, $T_{surface}$ significantly decreased to 35°C on asphalt and 42°C for brick pavers (Figure 18). The relatively high surface temperature of grass (location C; 46°C; Figure 18) was an indicator that water availability was low, which reduced the transpirative cooling capacity of this surface cover. The yellowing of grass observed during that day supports this interpretation.

Also air and globe temperatures were the hottest over unshaded asphalt. The air above the asphalt was 40°C (Figure 18), 1°C - 2°C warmer than over other surfaces. T_{globe} reached an astonishing 53°C (Figure 18), being 2°C - 3°C hotter T_{globe} than over other pavements or grass. Shade decreased T_{air} and T_{globe} equally above the car parks and grass, however, the magnitude of reduction was considerably smaller than on a mild or warm day. T_{air} was only 2% - 5% cooler in the shade than in the sun, with the largest effect for the old concrete at location D (-2°C; Figure 18). By contrast, the thermal conditions felt similar across the materials, with a reduction of about one quarter in 'feels-like' temperature in the shade (Figure 18).

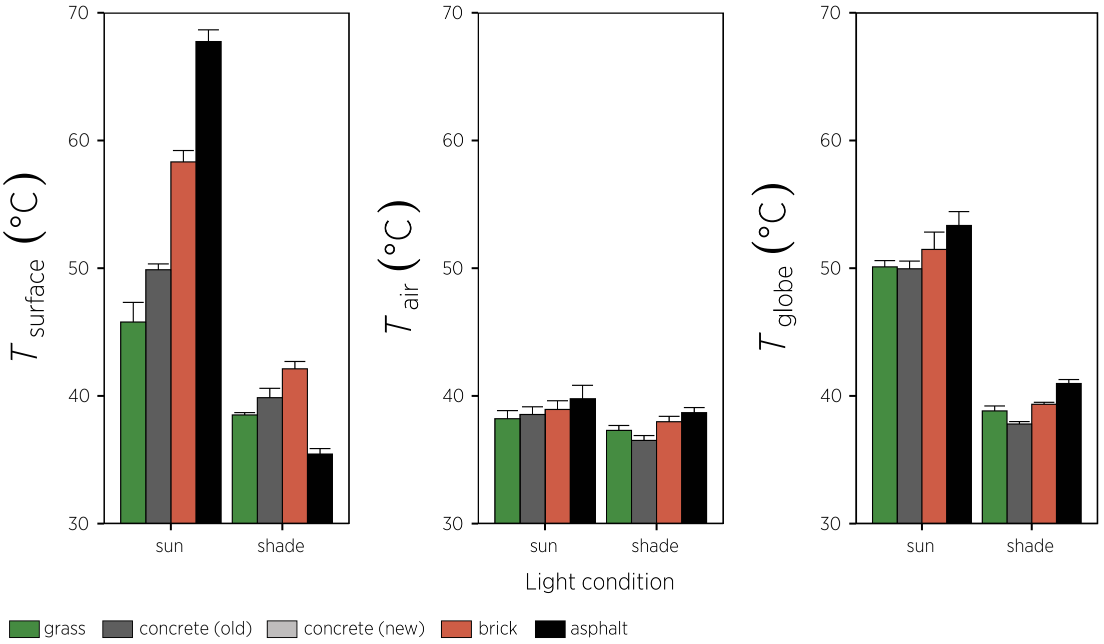


FIGURE 18: Surface ($T_{surface}$), air (T_{air}) and 'feels-like' (T_{globe}) temperature of asphalt, brick, two types of concrete, and grass measured on a hot day (24 January 2021) at the Liverpool Hospital. The description of elements in a plot is identical to those described in Figure 14.

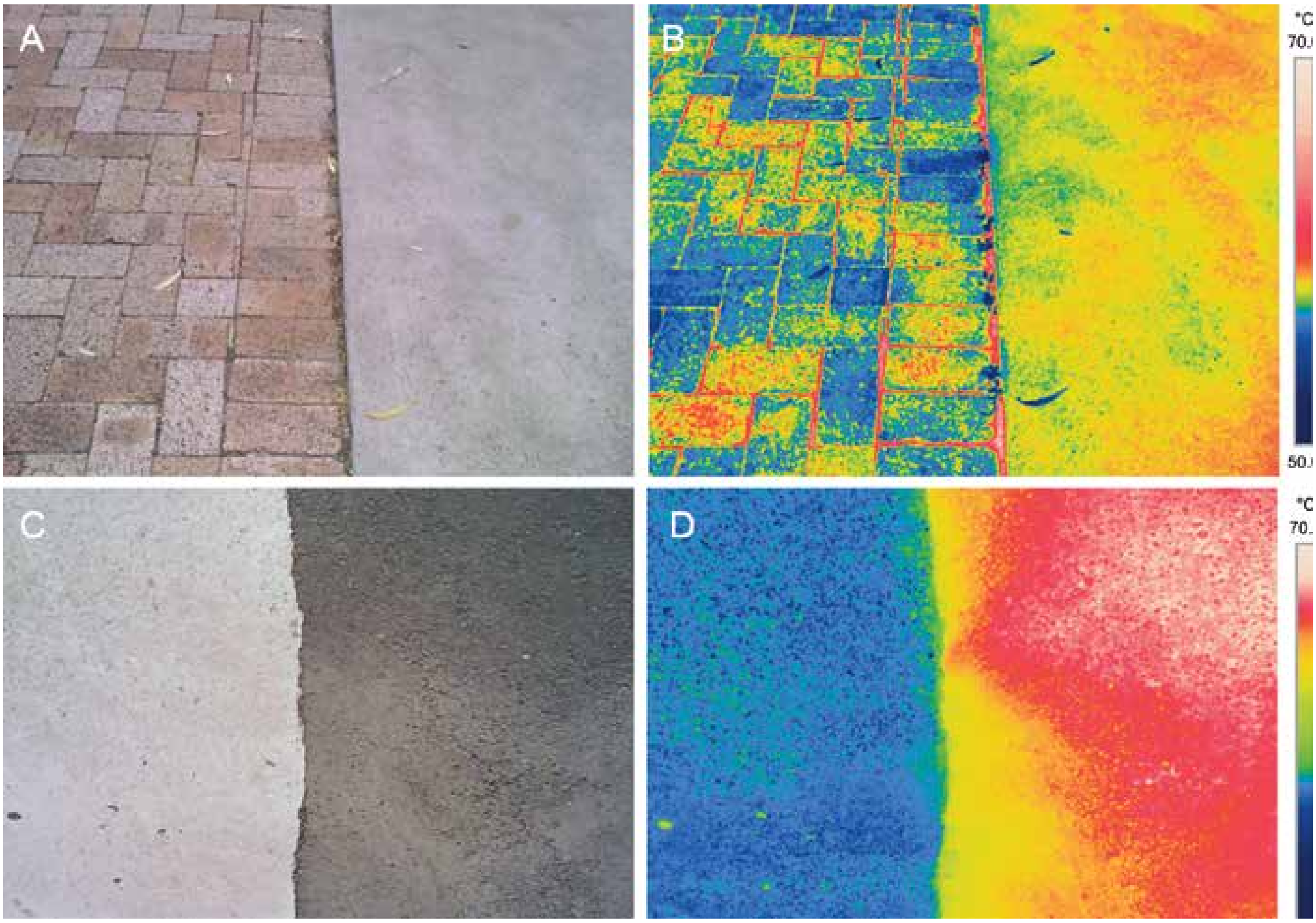


Figure 19 compares $T_{surface}$ for brick pavers, black asphalt and concrete pavements at locations B and F on the hottest day. Brick pavers were 1°C cooler than concrete; whereas the asphalt was 9°C hotter than concrete pavement.

FIGURE 19: Normal and infrared images comparing surface temperatures of brick and asphalt with the concrete pavement at locations B (a, b) and F (c, d). The images were taken at 15:34 (a, b) and 16:40 (c, d) on 24 January 2021. The scale on the right side indicates the range of surface temperatures represented by colour. Image © S. Pfautsch

These results are proof that unshaded, impervious pavement materials reach extreme temperatures on hot days, enhancing the warming effect on the surrounding air and the perception of temperature by humans. The importance of shade to prevent these hazardous conditions is underlined by data presented here.

Moreover, in sunlit car parks, the air temperatures measured at 0.30 m are systematically higher than the air temperatures measured at 1.1 m, while the vertical gradient in shaded car parks is negligible. At 0.30 m, especially in weak wind conditions (e.g., wind speed < 2 m s^{-1}), the air temperature can be even 0.8°C - 1°C hotter than at 1.1 m, because of the boundary layer in proximity of the surface (Table 5). In fact, the wind speed above a surface increases logarithmically with height because of the surface roughness. For instance, the air temperature over asphalt in the unshaded car park on 5 February 2021 was 31.4°C while it was 32.4°C at 0.30 m, with a wind speed of 1.2 m s^{-1} at 1.1 m and 0.45 m s^{-1} at 0.30 m. This happens for all types of land cover; even for grass, because it has higher roughness than a smooth car park and thus it reduces the wind speed more in proximity to its surface. However, for hot unshaded pavements it means that children, people in a wheelchair, and pets (e.g., guide dogs) have their core body closer to the pavement and are thus exposed to even higher air temperatures and lower wind speeds that can cool their bodies than other users of the car park. Obviously, the vertical temperature gradient is highly influenced by wind speed, and it must not be interpreted as a result only of the surface properties. However, it offers an appraisal of the significant microclimatic differences displayed vertically, in just 0.8 m (from 0.3 m to 1.1 m), further highlighting the importance of shade in car parks.

TABLE 5: Vertical temperature gradient (air temperature at 0.30 m minus air temperature at 1.1 m) for the different car parks.

Carpark type	Mild day (2 April 2021)	Warm day (5 February 2021)	Hot day (24 January 2021)
asphalt	0.3	1.0	0.8
brick	0.2	0.9	0.7
old concrete	0.4	0.8	n/a
new concrete	1.4	1.0	n/a
grass	1.1	0.8	0.6

MICROCLIMATIC VARIATION ACROSS CAR PARKS

The hottest absolute air temperature recorded during this study was 43°C, measured during the early afternoon of 26 January 2021 on the brick parking lot (location B). While incredibly hot, such singular data points are not useful when assessing if microclimatic differences could have their origin in the pavement types commonly used to build car parks. Here we approached this assessment using an analysis of continuous near-surface air temperature (T_{air}) measurements.

From the raw data, we extracted the mean maximum (T_{max}) and mean minimum (T_{min}) air temperature for the time interval during the late afternoon and early evening (16:00 - 20:00) for all 53 measurement days. This time interval was selected as it represents the time of day where absorption of incoming solar energy would decline but emission of stored heat from the ground surface would be high. The analysis showed that for T_{max} and T_{min} the sequence of hottest to coolest car park microclimate was: asphalt > brick > concrete (Table 6).

TABLE 6: Mean maximum (T_{max}) and mean minimum (T_{min}) near-surface air temperature for the hottest time of the day (16:00 - 20:00). The values are means (±SD) calculated across 53 days.

	Mean T_{max}	Mean T_{min}
brick	26.9 ±5.0	22.1 ±3.4
asphalt	27.4 ±5.1	22.3 ±3.4
new concrete	26.5 ±4.9	21.9 ±3.4

3.3 **SYDNEY MARKETS**

The *Solar Parking* project investigated the thermal environment across two car parks at the Sydney Markets in Flemington, 13 km west of Sydney CBD. The car parks were 200 m apart, and were located at the western and southern end of the site (Figure 20). One car park was at ground level in front of the Flower Markets (location A; Figure 21A). This car park was covered with conventional black asphalt. Approximately 1,000 m^2 of solar panels were installed in 2014 at 5-6 m over the ground. The second car park had a light-coloured concrete surface (location B; Figure 21B), and it was at the top of the multi-level parking building where 3,500 m^2 solar panels were installed in 2018 at 3-4 m above the ground. Both parking lots consisted of unshaded and shaded areas. Shade was predominately cast by solar panels. The surface ($T_{surface}$), 'feels-like' (T_{globe}) and near-surface air (T_{air}) temperatures were documented between 16 January and 27 March 2019 at both car parks.

FIGURE 20: Location of the solar car parks at the Sydney Markets. Car park A was covered with asphalt car park while car park B was at top ofthe multi-storey building and made from concrete. The overview map © Google Earth with the inlet image extracted from Nearmap (March 2019).

FIGURE 21: The solar car parks at the Sydney Markets. (A) Car park A was covered with asphalt and it was located between the main entrance and the flower market. (B) Car park B had a concrete surface and it was located at the top of a multi-storey parking lot. Image © S. Pfautsch

SURFACE TEMPERATURE

$T_{surface}$ of the asphalt at location A and concrete at location B were collected in the sun and shade. Additionally, images of sunlit and shaded black and white cars were taken to capture the cooling effect of the solar panels on stationary vehicles. All images were taken with a handheld infrared camera (T640, FLIR Systems, Wilsonville, United States) between 13:00 and 14:30 on 16 January 2019. The maximum ambient air temperature that day ranged between 35°C and 39°C. A total of 51 images were taken, from which 65 individual measurements were extracted using the FLIR Tools software.

Unshaded asphalt at location A had the hottest $T_{surface}$, reaching on average 66°C (Figure 22A, B). This was 16°C - 19°C hotter than the unshaded concrete surface at location B (Figure 22C, D). Once shaded, $T_{surface}$ of asphalt and concrete cooled considerably (Figure 22). The shade of solar panels reduced the $T_{surface}$ of asphalt to 35°C, representing a cooling effect of 47%. At the same time, shaded concrete had a $T_{surface}$ of 34°C, which was 13°C lower temperature than in the sun (cooling effect of 27%).

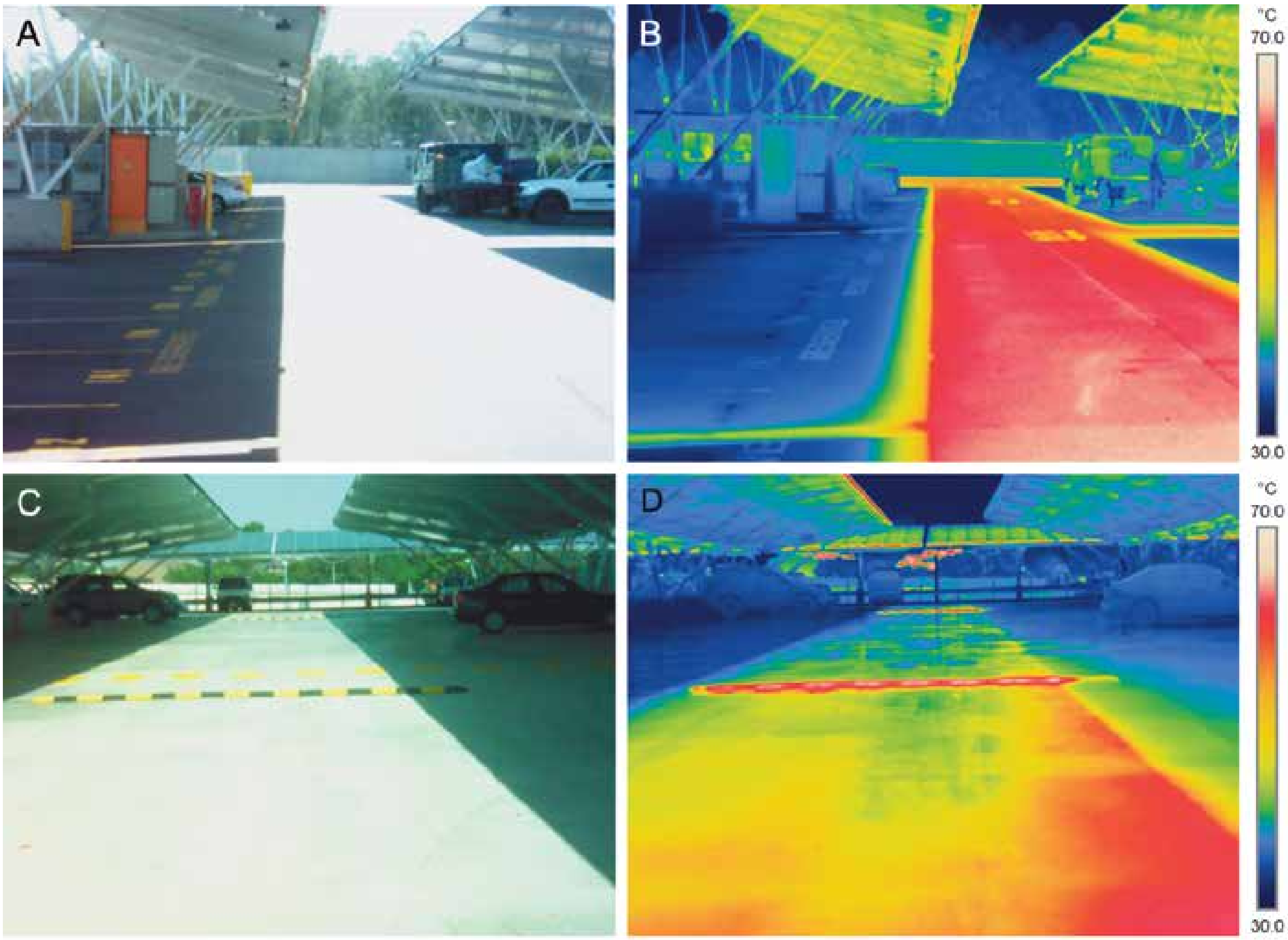


FIGURE 22: Normal and infrared images of car parking surface materials at location A (black asphalt, panels A and B) and location B (light-coloured concrete, panels C and D) at the Sydney Markets. Infrared images on the right show surface temperatures in the sun and in the shade. The images were taken at 14:28 at location A and 13:27 at location B on 16 January 2019. The scale on the right side indicates the range of surface temperatures represented by colour. Image © S. Pfautsch

A black car parked in the sun showed an average $T_{surface}$ of 68°C (Figure 22A, B), 2°C warmer surface temperature than the sunlit asphalt. By contrast, an unshaded white vehicle reached a $T_{surface}$ of 48°C (Figure 22C, D), 20°C cooler than the black car in full sun. When solar panels shaded the stationary vehicles, the $T_{surface}$ of the black car was reduced to 37°C (cooling effect of 46%) and that of the white car to 36°C (cooling effect of 25%) (Figure 22E, F). These observations underline that shading dark surface materials and vehicles will have a greater cooling effect when compared to shading lighter materials.

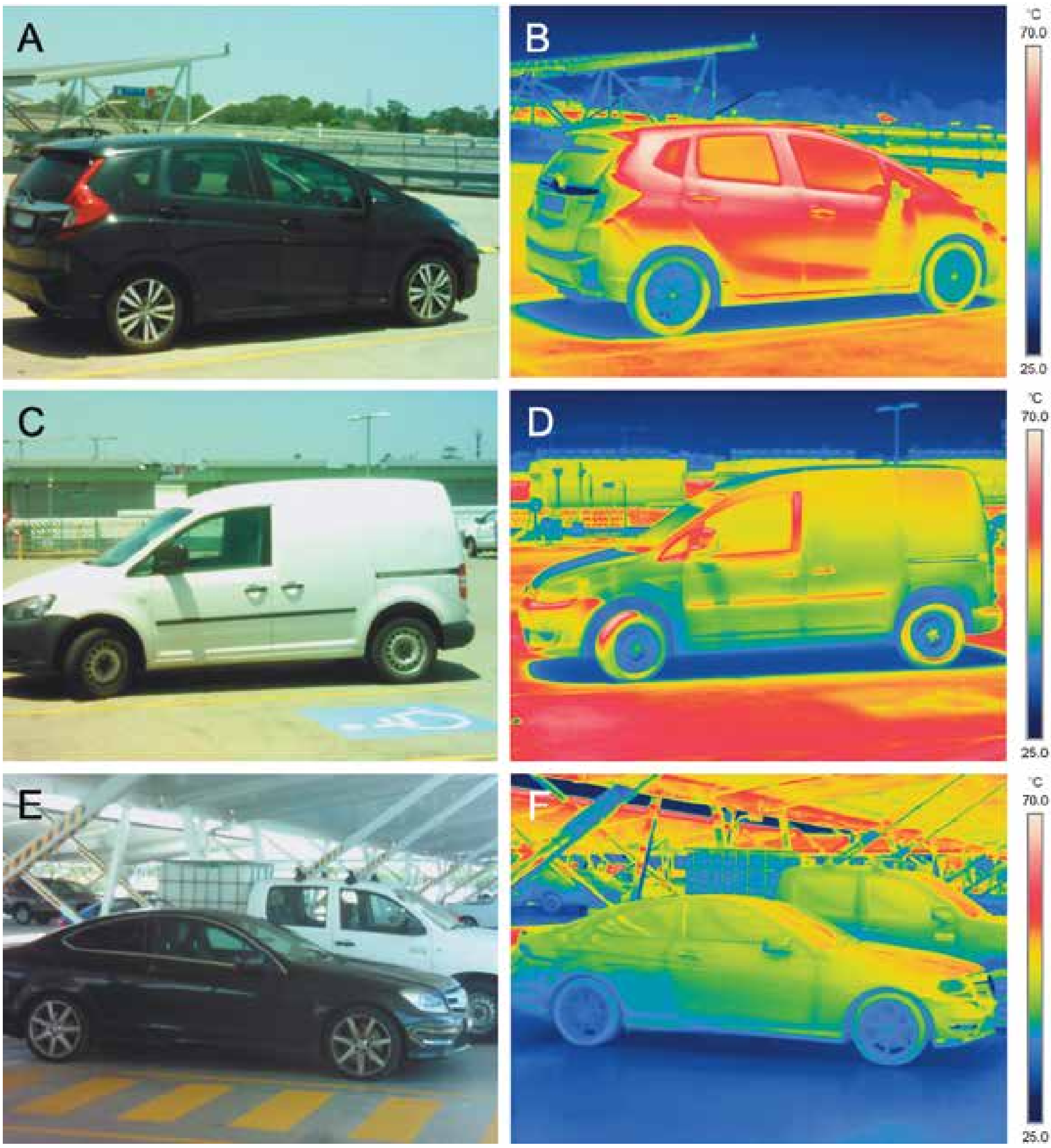


FIGURE 23: Normal and infrared images of surface temperatures measured on the exterior of black and white cars in full sun (Panels A-D) and in the shade of solar panels (Panels E and F) at the Sydney Markets. The images were taken around 13:30 on 16 January 2019. The scale on the right side indicates the range of surface temperatures represented by colour. Image © S. Pfautsch

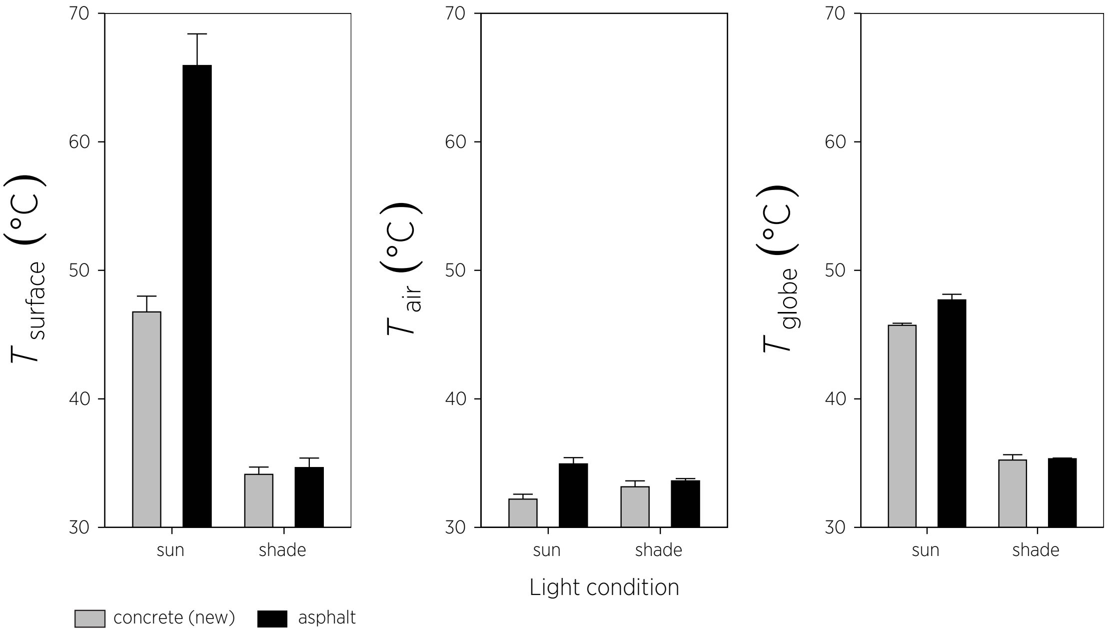


FIGURE 24: Surface ($T_{surface}$), air (T_{air}) and 'feels-like' (T_{globe}) temperature of concrete and asphalt on 16 January 2019 at the Sydney Markets. The measurements were collected in the sun and shade. The bars represent a mean of $N = 10$ ($T_{surface}$) or $N = 5$ (T_{air}, T_{globe}) and the error bars indicate +1 standard deviation.

AIR AND 'FEELS-LIKE' TEMPERATURE

Measurements of T_{globe} and T_{air} were collected 1 m above car park surfaces using a single Kestrel Heat Stress Tracker. Data were collected between 13:00 and 14:30 on 16 January 2019 and represent an integrated measurement over at least 10 minutes.

T_{air} above unshaded asphalt was 35°C and 3°C cooler over unshaded concrete (Figure 24). In full sunlight, T_{globe} over asphalt was 48°C and 46°C over concrete (Figure 24). Shade from solar panels efficiently decreased the T_{globe} by more than 10°C but it had a negligible effect on T_{air} at both car parks (Figure 24).

FIGURE 25: Examples of positioning the custom-made loggers underneath the solar panels at locations A and B. Panel A: shade at location B. Panel B: Full sun and location B. Panel C: Shade at location A. Image © S. Pfautsch

NEAR-SURFACE AIR TEMPERATURE

The near-surface air temperature (T_{air-c}) was continuously recorded between 17 January and 27 March 2019 using 12 custom-made loggers containing the Tempmate temperature sensor (Figure 5B). The same type of instrument was used in the *Hospital project* (section 3.2). Six loggers were distributed across location A and also location B. At each location, the six loggers were positioned 20 m apart and installed 3 - 3.5 m above the ground in the sun (N = 3) and shade (N = 3). Examples of mounting loggers underneath the solar panels and in the sun are shown in Figure 25A-C. A total of 120,960 individual near-surface air temperature measurements were recorded and analysed.

Given the daytime and nighttime differences between the car parks in sections 3.1 and 3.2, here we used the same temperature derivatives to describe the thermal conditions in the *Solar Parking* project. The daytime parameters were calculated between 10:00 and 18:00, while nighttime hours were from 22:00 to 06:00. Firstly, we computed means for each day across the three replicate loggers, and then these values were averaged across the 70 measurement days. Additionally, one absolute maximum daytime and one absolute minimum nighttime temperature were extracted from the loggers for each day. The absolute values were then averaged across the 70 days. We also counted the number of days with hot (≥35°C) and extreme (≥40°C) air temperatures.

The hottest day recorded in this project was 18 January 2019 where the 24 h mean air temperature did not fall under 29°C. Also, the highest individual temperature with 43.6°C was measured at the unshaded asphalt (location A) at 16:50 on 31 January 2019. The lowest $T_{air\text{-}c}$ of 13.3°C was measured during the night on unshaded concrete (location B).

In general, the $T_{air\text{-}c}$ during the day was 1°C warmer over unshaded asphalt compared to unshaded concrete (Table 7). The coolest $T_{air\text{-}c}$ were consistently measured underneath the solar panels at location B. While $T_{air\text{-}c}$ was generally hotter in sunlit car parks during the day, they were slightly cooler during the night (0.6°C at location A and 0.5°C at location B) compared to thermal conditions underneath the solar panels (Table 7). The 'blanket effect' of solar panels, preventing dissipation of daytime heat into the night sky, increased mean nighttime T_{min} by 0.9°C over asphalt and 0.6°C over concrete (Table 7).

TABLE 7: Mean near-surface air temperatures measured at the asphalt (location A) and concrete (location B) car parks at the Sydney Markets between 17 January and 27 March 2019. Data shown are means (±1 Standard Deviation) of N = 70, with daytime values calculated between 10:00 and 18:00, while the nighttime temperature was calculated using measurements recorded from 22:00 to 06:00.

	asphalt (location A)		**concrete** (location B)	
Parameter	**sun**	**shade**	**sun**	**shade**
daytime $T_{air\text{-}c}$ (°C)	28.5 ±4.2	27.6 ±3.9	27.4 ±4.0	27.0 ±3.9
daytime T_{max} (°C)	32.1 ±4.9	30.2 ±4.5	30.8 ±4.7	29.8 ±4.4
nighttime T_{air} (°C)	21.7 ±2.4	22.3 ±2.2	21.4 ±2.2	21.9 ±2.2
nighttime T_{min} (°C)	20.1 ±2.4	21.0 ±2.3	19.8 ±2.4	20.4 ±2.2

Although air temperatures were slightly warmer under the solar panels at night, the cooling benefits provided by the shade structures during the day were far more beneficial for car park users. Under their shade, the number of hot (≥35°C) and extreme heat days (≥40°C) were nearly equal (12 and 1 at location A, 11 and 1 at location B, respectively). However, the type of surface material mattered when shade was absent. At location A, 28 hot days and 6 extreme heat days were documented, whereas only 20 and 4 days of these very hot days were recorded at location B. Given that the two locations are just 200 m apart, the more frequent extreme thermal conditions on asphalt indicate that this material is less desirable for unshaded car parks. We caution that besides the surface material, also the elevation of location B and associated greater exposure to cooling breezes may have contributed to these results. Here, further research would be required to disentangle the thermal effects of surface types from those related to air turbulence.

Findings from the *Solar Parking* project clearly showed that light-coloured concrete performed better to heat-retaining asphalt because it constantly had lower surface temperatures and ultimately provided greater human thermal comfort. Shade was equally efficient in reducing surface temperatures of both car parks during the day; however, the solar panels acted as barrier to convection of warmed air during the night, keeping air temperature under the panels slightly higher compared to free sky conditions. These effects are far outweighed by substantial daytime cooling and the concurrent production of regenerative energy.

4. CAR PARK DESIGN REGULATIONS & GUIDELINES, & COMMITMENT TO ENVIRONMENTAL PERFORMANCE

Before any changes towards cooler car parks can be implemented, it is important to understand the current regulatory frameworks and guidelines that have resulted in the types of at-grade parking lots being built across urban fringe zones and elsewhere in metropolitan regions. Documents used for the following sections are listed in Appendix 1.

4.1 MINIMUM STANDARDS

Currently, car park designs are primarily regulated by *Australian Standard 2890.1* (AS2890). Although not in itself a regulatory requirement, AS2890 has been adopted as the minimum regulatory requirement by, among others, the NSW Government's Roads and Maritime Services (RMS). It is also accepted as the de facto standard by other agencies.

AS2890 does not offer any specific guidance around energy use, thermal comfort or other related aspects of environmental performance. At the outset of the document, AS2890 establishes its confined scope:

> **"The success of a parking development requires an efficient design… Consideration must be given to the speed and quality of parking service, traffic circulation, access to and from the street, the external traffic network, car manoeuvring, and convenience for the drivers and pedestrians, including people with disabilities."**

Under Section 2.3.1, 'design coordination', the purpose of standardising car park design is stated to be to minimise disruption to traffic, maximise pedestrian safety, and provide for more universal accessibility. This is achieved primarily through avoiding conflicts between traffic streams and with pedestrians, as well as providing parking and circulation spaces accessible to people with disabilities.

The reference to 'pedestrian safety' (albeit relating to collisions with vehicles) and 'accessibility' (albeit relating to people with disabilities) could justify minimum standards to mitigate against high ambient temperatures reached in open car parks, particularly where it relates to safety of users, or even discriminatory access to those susceptible to high temperatures. This, though, only represents an indirect approach to justify reducing UHI effects of car parks. However, it is clear that the primary function of AS2890 is to prescribe dimensions for parking spaces, circulation areas, and access points (between the car park and surrounding roads).

While silent on environmental performance generally, let alone UHI effects specifically, one notable overlap, in Section 4.8, is the requirement that:

> **"When providing trees and shrubs, safety aspects such as sight distance to both pedestrians and other vehicles shall not be compromised at any time during the life of the plantings."**

The same section specifies, as a note, that "judicious placement of trees provides shade and screening… and is to be encouraged". There is no other mention of shade, or temperature – as it relates to health and safety of pedestrians or vehicle users or otherwise.

It is worth noting that 'sight distance' represents one potential barrier to provision of non-compulsory shading devices (whether landscaping or otherwise). While not expressly prohibited, the perceived risk of such devices complicating compliance with compulsory standards could reduce their use, particularly as no guidance is readily available on how to avoid conflicting these two objectives (i.e., mitigating high temperatures and maintaining clear sight lines).

Additional minimum standards are also outlined in the *National Construction Code* (NCC), in particular relating to lighting, ventilation (for enclosed car parks), fire control and sprinklers, and accessibility. However, like AS2890, there are no standards mitigating against high ambient surface or air temperatures.

The NCC does have more extensive standards for environmental performance and thermal comfort in Part J. However, this part of the NCC makes no explicit reference to car park standards, with the single exception of maximum energy used for artificial lighting in car parks.

In short, there is little prescriptive guidance on the potential for poorly designed car parks to reach temperatures, contributing to the UHI effect, and so creating a risk to human health or environmental damage.

4.2 **OTHER GUIDELINES AND OTHER NON-PRESCRIPTIVE POLICIES**

Beyond minimum standards, there exist a range of car park design guidelines that are not compulsory. This includes guidelines from NSW Health, policies employed by other agencies (particularly Transport for NSW (TfNSW)), and design controls that local councils apply to local development.

Among these policies, Transport for NSW have operated under its *Sustainable Design Guidelines* for over a decade, with the most recent editions (version 4) released in 2017. Although not mandatory outside TfNSW projects, it offers more clear guidance on how to improve the environmental performance of car park developments. The guidelines cover projects other than car parks, but as commuter car parks are a common component of TfNSW projects, the guidelines are relevant. Among other things, the guidelines outline requirements to address:

- Climate change – specifically requiring a climate risk assessment, including risks of extreme heat events and so is relevant to car park temperatures;
- Energy consumption – including during operation. A reference is made to Appendix F, Section 3 'Covered and Uncovered Areas Specific Requirements', which is not included in the online version and so not reviewed. But, insofar as higher temperatures increase energy loads of cars, it would overlap;
- Water usage – water sensitive urban design is expected, including permeable surfaces and onsite water retention, which would have a bearing on tree coverage and other vegetation, and potential for evaporative cooling;
- Urban design principles – reference is made to an 'INTERIM VERSION Multi-level and at-grade Commuter Car Parks urban design guidelines'. Although this is not publicly available and so not reviewed here, it is worth noting that it does not (in the context of these sustainability guidelines) pertain to environmental performance or health and safety. However, it does guide landscaping and related principles of user amenity, which would overlap with thermal comfort and environmental performance.

One limitation to these guidelines is they offer *processes* to identify ways to improve environmental performance, but not specific measures in most cases. This is consistent with similar guidelines (such as Greenstar, discussed below), where the most appropriate measures will be project specific and so impractical to outline in a guideline applied across all projects. However, insofar as it makes such processes compulsory, it increases the likelihood of environmental performance being improved, and measures like shading in car parks, on-site water retention, use of high albedo materials, or other mitigating strategies against the UHI effect, are being adopted.

It is worth noting that other policies and guidelines that seek to improve health and sustainability related to developments generally, offer little to guide car park design. The primary focus of such documents is to discourage car usage, by reducing car parking provision or, at least, reducing its prominence.

For example, the Green Building Council of Australia's *Greenstar* system offers points for reducing car parking provision, and for providing alternatives – such as bicycle facilities or similar (see "Sustainability Impacts from Transport – credit criteria"). Yet the points system is silent on how some car parks would have a lower environmental impact than others. While other aspects of the Greenstar system offer points for – and so guidance on – energy consumption (which could include mechanical cooling load of hot vehicles in car parks) – there is no guidance on better car park design in this respect.

Similarly, the NSW Health's *Healthy Built Environment Checklist* focuses on reducing car parking as a means to encourage active transport alternatives, prompting developers to ask (page 98):

> **"Does it encourage the reduction of car parking spaces in urban areas (particularly where there is good public transport available) including the re-allocation of car parking spaces for bicycle parking and cycling routes?"**

Under the topic of open space and natural features, the checklist highlights the benefits of shade – natural and otherwise – and the risks of extreme heat. However, this is not a consideration of car parking.

Finally, local councils almost universally establish standards for car parks proposed as (or as part of) private developments, through their *development control plans* (DCPs). Like internal TfNSW guidelines, these plans offer a framework for internal assessment of project design.

For example, landscaping guidance overcomes the above-mentioned imbalance with sight distances in AS2890:

> **"An outdoor car park with 20 or more car parking spaces must include at least 1 tree per 10 car parking spaces [and any] tree must be a single trunk species to allow a minimum visibility clearance of 1.5m measured above natural ground level…" (Liverpool DCP 2008, page 92)**

Tree coverage is recognised as a means to improve shading, while also allowing for objectives related to habitat quality and other environmental objectives to be achieved:

> **"Trees should be planted to achieve 50% shading of the car park at 10 year maturity. Appendix 1 provides a list of the tree species recommended by Council, with native species favoured." (Blacktown DCP 2015, Part A, page 42)**

It is worth noting that, of the western Sydney local councils DCPs reviewed, most explicit focus is on tree planting as a means of providing shading, and typically requires landscaping plans to be included with any proposal for open car parks. This could be at the expense of incorporation of artificial shading, where that is more appropriate. It is also worth noting that heat is not always a driver of landscaping requirements. Consequently, landscaping might not be optimised to reduce heat.

A final limitation of DCPs, worth noting, is that they are not consistent among local councils. While the DCPs reviewed were not conflicting in their controls, and all advocate for similar 'best practice' when it comes to car park design, no single DCP can be seen as a singular source of guidance in relation to 'cool' car park design.

4.3 **POLICY CONCLUSIONS AND CALL FOR ACTION**

Overall, there is no obligation for government infrastructure projects or private development to implement heat-responsive design elements when constructing at-grade car parks. Australian and state guidelines regarding car park environmental performance, to date, are a 'light touch', with no prescriptive standards and heat mitigation strategies in place. This policy vacuum does, however, allow different organisations to chart their own problems and policy solutions. From a subsidiarity perspective - that the matter of car park design should be handled at the organisational level, rather than by a centralised authority - allows for discretion over asset management strategies, resource allocation and prioritisation.

Given solutions will be project-specific, it could be preferably for any requirement to simply be value statements at an organisational or project scale, regarding environmental performance. However, a lack of appropriate incentives to implement energy efficiency measures could significantly hinder the realisation of progressive and effective heat mitigation strategies. Competing budgetary priorities, upfront capital costs, desired payback periods, and difficulties measuring wider public and environmental benefits, along with split incentives, seem to be the primary reasons as to why heat mitigation solutions have not been implemented.

Sydney Markets' solar program of its car parks (see chapter 3) is a good illustration of establishing an effective sustainable asset and portfolio management strategy at a whole-of-organisation level. Particularly as it integrates environmental performance with financial benefits. By installing photovoltaic panels over the multi-level parking lot and the main car park for the Flower Markets, the PV panels will generate considerable megawatts hours of electricity per year which are fed back into the internal electricity grid of Sydney Markets. This type of intervention is therefore mutually reinforcing across financial and environmental objectives, as it allows the organisation to make energy savings, and reduce its size and capital cost of overall electricity requirements and systems. By covering existing car park structures, this approach also maximises land efficiency whilst creating a more comfortable, cooler environment for car park users. Such a systems approach effectively creates a host of ancillary benefits that increases the project's ROI and payback on capital investment. It creates an incentive to adopt sustainable measures which offer an environmentally conscious alternative to outdoor car parks, which exhibit temperatures risking human health, and provides a small step towards creating sustainable cities.

The problem, though, is that without appropriate guidance, incentive or requirement from beyond the organisation - essentially through government regulation - too few organisations are following the Sydney Market example. As such, there remains a role for a less 'light touch' regarding environmental performance of car parks. The lack of clear guidelines highlights the need for comprehensive research collaborations among academics, government organisations and industry. These innovative projects must not only develop best practice guidelines for heat-responsive car park design, but must also inform and support the partner's short-, medium- and longer-term strategic planning around climate risk mitigation and resilience strategies.

5. HOW TO COOL CAR PARKS

The empirical evidence provided in this report can inform strategic decisions in car park design. For example: it presents a process for identifying which existing car parks are reaching temperatures that create a risk to human health and environmental damage, which to therefore prioritise for retrofitting, and which sustainability options to implement, not just for existing car parks but new car park developments. Furthermore, this analysis can be readily compared against the bundle of low and high ROI projects across an organisation's asset management portfolio to allow informed strategic decision-making.

Existing car parks have an immense footprint across all public sector organisations, including educational, police, transport, health, local government establishments as well as those in private and NFP ownership. Whilst there is growing support for improving car parks' sustainability outcomes to combat climate change impacts and health risks, there exists, to date, limited:

- comprehensive and systematic research on auditing the temperature of public, private and NFP sector organisations' car parks,
- detailed car park design guidance relating to heat at all tiers of government,
- supporting information around best practice on sustainable car park design, and particularly relating to heat,
- comparative cost/benefit analysis of different sustainability options that account for short and long-term financial, environmental, social and health considerations,
- strategic advice on devising sustainable asset management strategies that encompass a bundle of options, which have wider ancillary benefits for the organisation,
- in-depth analysis on how to statutorily regulate and/or incentivise company action to introduce measures and address the sustainability challenge.

This report begins to fill some of these gaps.

The warming effect of car parks is the combined effect of surface materials and the presence or absence of shade. The cooling strategies introduced in this section include using permeable and reflective surfaces, artificial and natural shade and Water Sensitive Urban Design (WSUD). These approaches are the most efficient in reducing heat stored within parking lots (Cheela et al. 2021) because they lower the surface temperatures, improve the local microclimate and increase human thermal comfort (Taleghani 2018; Sen et al. 2020). This section provides a good starting point to combat urban warming and create more heat-resilient cities.

5.1 NATURAL SHADE

Vegetation reflects direct solar radiation and creates shade, effectively reducing surface temperatures of pavements, vehicles and improving human thermal comfort (this report, but see also Bowler et al. 2010; Cheela et al. 2021; Erlwein and Pauleit, 2021; Sharifi et al. 2021). Scott et al. (1999) investigated the occupancy of unshaded and shaded parking lots on hot summer days, and clearly showed that users prefer to park underneath the tree canopy. Moreover, the shading of impervious materials can significantly extend pavements' life span, reducing maintenance costs associated with repairs and resurfacing (McPherson and Muchnick, 2005). Natural shade can be provided by trees and plants climbing on support structures. However, vegetation will require occasional maintenance and potentially irrigation - which require additional resources. Figure 26 depicts examples of conventional car parks with high canopy cover providing considerable shade and cooling benefits.

FIGURE 26: Examples of car parks with many mature trees creating a significant canopy cover in the northern part of Sydney. A: car park at CSIRO (Marsfield, NSW). B: car park at the Macquarie University (Macquarie Park, NSW). Images extracted from Nearmap (December 2021).

Trees can lower ambient air temperature through transpiration, apart from providing shade and reducing the surface temperatures underneath the crowns. Transpirative cooling allows trees to regulate leaf temperature and also provide air cooling through latent heat flux cooling, which in turn lowers the air temperature inside and around the crown Trees need access to water for transpiration to occur, particularly at the planting stage but also during heatwaves. Sanusi and Livesley (2020) showed that insufficient water availability on extreme summer days might lead to foilage loss, minimising the thermal benefits of trees. However, some species continue to transpire during heatwaves when access to water is not limited (Drake et al. 2017) whereby they continue to cool air temperatures. Thus, trees must be well-watered to maximise their cooling benefits and create a beneficial microclimate. This can be achieved through an active irrigation system or passively using tree pits and trenches.

An important aspect of the quality and area of shade provided by trees is the time they need to develop the desired crown density and size. Figure 27 shows an example of a heat-responsive car park in western Sydney. Black asphalt was replaced with light-coloured concrete for driving surfaces and parking areas were covered with locally-sourced crushed and compacted sandstone. These changes reduce surface heat and the permeable nature of the parking surfaces allows stormwater to seep into the ground where it becomes plant-available. However, even when implementing these strategies, the aerial images show that six years post-construction, crowns of newly planted trees remain relatively small and do not block solar radiation effectively. During the 6 year-period, the average ground-projected crown area of newly planted trees increased from 0.49 m^2 to 5.55 m^2, ranging from 1.53 m^2 to 25.15 m^2 which reflects species differences. Only incorporating the existing mature trees in the design of the car park has resulted in lowering surface (and car) temperatures for several years.

FIGURE 27: A car park made of locally sourced crushed sandstone in Bungarribee Super Park in Western Sydney Parklands, NSW. The two images depict the car park shortly after construction (A: October 2015) and six years later (B: August 2021). Images extracted from Nearmaps.

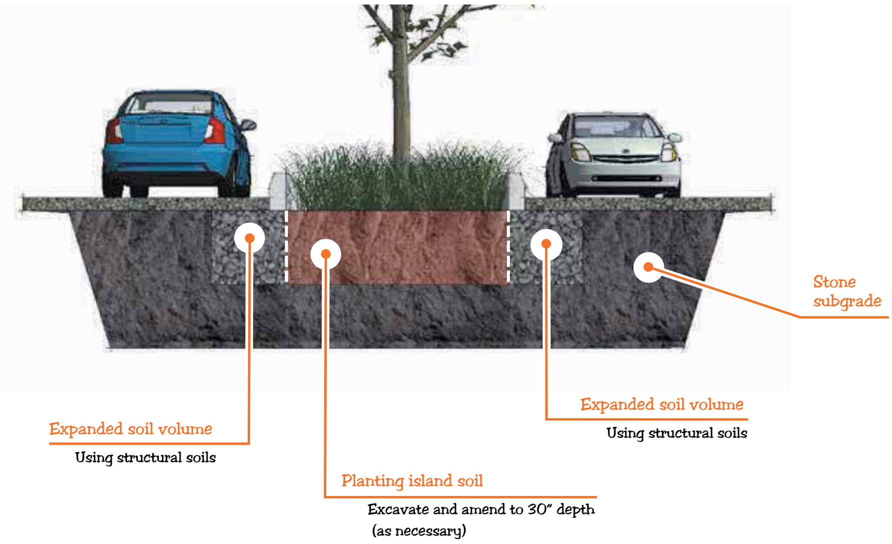
In the City of Belmont (Perth, WA; https://citygreen.com/), a car park was re-designed to test whether increasing the soil volume and providing water storage would improve tree growth and thus shading of paved surfaces at parking lots. London Plane trees were planted using two methods, the conventional open ground (method 1) and soil vault systems in two trenches (method 2) (Figure 28A). Trees were not irrigated, relying solely on rainfall. Over time, the growth was assessed to compare which approach provides better tree growth and canopy shade. Although installing a vault system (method 2) was more expensive, those trees provided substantially more shade than the trees that were planted using the conventional method (Figure 28B), providing a significant financial and environmental ROI. Our analysis of crown size of trees planted in the vault system showed an increase from a mean of 6.6 m^2 in 2013 (Figure 28A) to 57.6 m^2 in 2019 (Figure 28B). Compared to crown area development of trees planted in the car park in western Sydney (Figure 27B), trees supplied with water in vaults had 10-times larger crowns over the same 6-year period.

FIGURE 28: A car park in Forster Park in the City of Belmont, Perth, WA. The two images show trees after planting in January 2013 (A) and well-grown tree crowns in February 2019 (B). These images illustrate the effect of the planting method on the size of the canopy. 1: Trees were planted traditionally in the open ground. 2: Trees planted in the soil vault system. Images extracted from Nearmap.

As shown in the *Hospital* project (Section 3.2), tree shade significantly lowered surface temperatures of asphalt (38% - 51%) and brick (28% - 36%) driving and parking surfaces. However, trees were mainly located at the edges of the parking lot, so only a small section was provided with shade cooling while a substantial area was still exposed to sunlight. Restricting trees to car park boundaries is a typical design to maximize the space used by vehicles. Thus, the tree location inside the car park should be carefully considered at the planning stage.

Several researchers have investigated the optimal positioning of trees in car parks to increase the shaded area, achieve maximum cooling and thus improve site microclimate. Ideally, many trees should be planted between the individual parking rows (Bajsanski et al. 2016; Milošević et al. 2017; Sharifi et al. 2021). Lin et al. (2021) provides the best arrangement of vegetation to improve temperatures for car parks in mid-rise residential areas. However, positioning large trees can be difficult and take up additional parking space, which can be problematic in some cases. However, careful planning will consider not only tree crown development over time, but also address soil volume available for roots.

To ensure optimal growth conditions for trees in car parks, they should be planted in a designated section with appropriate soil volume and other technological applications to protect the root system (Appleton et al. 2009; Sharifi et al. 2021). Options include (after MCPC, 2015):



» Structural soils that expand the soil volume for planted trees. This additional section of growing media allows for undisturbed root growth beyond the planting island while supporting the weight of parked vehicles (Figure 29; MCPC, 2015). Structural soils are usually a mixture of stone (80%) and loamy soil (20%).

FIGURE 29: Example of expanding soil volume under a car park by addition of structural soil. Image © MCPC (2015)

» Plastic modular support structures (e.g., Silva Cell, Arbor Cell) filled with soil to provide an extended root volume for trees beneath the parking area (Figure 30). Such solutions also create additional space to store and retain stormwater, and minimise soil compaction by vehicular traffic. These systems are particularly suited when planning for large shade trees.

FIGURE 30: Example of a modular support structure underneath a parking lot. Image © deeproot

- Trenches with trees growing in the same continuous pit allow for undisturbed root penetration while the large void underneath collects rainwater to maintain vegetation growth. This system can be used at the edges, as a divider between parking bays or along footpaths within the car park area. Figure 31 shows an example of a tree trench between two sets of parking sections. This solution applies principles of Water Sensitive Urban Design (WSUD), described in more detail in section 5.5.

FIGURE 31: Acer trees in pits within a continuous trench between the parking bays at Jamison Group Centre in Canberra, ACT (Image: https://www.cityservices.act.gov.au).

When planting trees is not possible, climbing vegetation on support structures is an alternative to provide natural shade for parking lots. In Darwin, this type of support structure was erected over a busy inner-city street, spanning 55 m in length (Figure 32A). This structure was installed in 2018, and the cooling capacity is investigated as vines start to grow into the structure. Preliminary results show air temperature reductions of 0.4°C in 2019 and 0.7°C in 2020 (UNSW, unpublished). It is expected that the cooling efficiency of the structure will increase as plants grow. Less expensive options for support structures also exist (e.g., Urban Canopee, www.urbancanopee.com) to provide plant canopy in parking lots where trees cannot be planted (Figure 32B).

FIGURE 32: Examples of climbing plants on pergolas used to create natural shade for parking lots. A: a 55 m long pergola used to shade road and car park surfaces on Cavenagh Street in Darwin's CBD. Image © Michael Franchi (https://www.abc.net.au). B: Urban Canopee used on a car park at the Général Leclerc square in the City of Le Quesnoy in France (www.urbancanopee.com).

It is crucial to take into account other factors when considering plant shade for car parks:

» The efficiency of natural shade depends on plant species and their crown/leaf characteristics (Speak et al. 2020; Cheela et al. 2021). Tall trees with dense crowns provide the best shade and surface cooling during the daytime, so they should be considered particularly at car parks with heat-retaining materials such as black asphalt.

» Dense tree crowns may lead to slightly warmer air temperatures at night (up to 1°C in Sydney, see Wujeska-Klause and Pfautsch, 2020; up to 2°C in Davis, California, see Scott et al. 1999).

» As plants need time to grow, selecting fast-growing species that reach full shading potential early may be desirable (Sharifi et al. 2021).

» Access to sufficient water is essential to reach the desired shading and cooling potential, particularly for trees in the first years after planting and during heatwaves (Drake et al. 2018).

5.2 ARTIFICIAL SHADE

Similarly, to trees and climbing vines, artificial shade structures also efficiently reduce the heat in car parks. Most of these shade structures do not require maintenance but come with a considerably high installation cost. Support structures are generally made from powder-coated steel. Materials used to provide shade include:

» High-Density Polyethylene (HDPE) shade cloth

» Polyvinyl chloride (PVC) tensile membranes or open weave mesh

» Polytetrafluoroethylene (PTFE) tensile membranes

» Metal roofing (i.e., Colorbond)

» Solar panels

FIGURE 33: Examples of artificial shade structures that can be implemented within car parks. Images A-C © MakMax Australia (https://www.makmax.com.au/). Image D © Agnieszka Wujeska-Klause.

Most of these materials have the added benefit of blocking harmful Ultraviolet (UV) radiation. A study conducted across playgrounds found that various fabrics can block between 95% and 100% of UV (Pfautsch and Wujeska-Klause, 2021b). Thus, the artificial structures provide cooling through surface shading and protect car park users from exposure to harmful radiation. On the downside, and unlike well-watered vegetation, these materials do not provide transpirative cooling and associated cooling of ambient air.

A combination of vegetation and manufactured shade can be an optimal solution to provide instant shade at the time of construction and maximise the shading of parking surfaces over time. While cooling benefits generally increase with the size of the shaded area, the effectiveness of manufactured shade decreases when the sun is lower on the horizon, especially at the hottest time of the day (Turnbull and Parisi 2006; Jay et al. 2021). To reduce this unwanted effect, strategic planting of trees and tall shrubs at the perimeter of shade structures will improve the efficacy of cooling throughout the day (Turnbull and Parisi 2005).

At the same time, the extensive dimensions of artificial structures may restrict the airflow, trapping warmth underneath the structure. Such effects have been documented in Section 3.3). It is recommended that provisions for venting of warmed air are made.

Manufactured shade materials such as cloths, tension membranes and metal roofing are relatively easy to install in new and existing car parks. Depending on the available space, they can be installed in a specific section (Figure 33A, D) or over the entire parking lot (Figure 33B, C). Reflective fabrics are the most efficient in improving human thermal comfort (Pham et al. 2019). Thus, light colours for shade sailsor sheet metal are recommended to increase reflectance, minimise heat absorption and subsequent radiation of sensible heat into the covered car park space.

Photovoltaic panels are an increasingly popular shading solution in car parks due to the added benefit of energy production and dual use of space. Solar panels are very effective in surface cooling. We documented a reduction of surface temperatures by 47% in Section 3.3 of this report. Similar to sail- or sheet-based shade solutions, support structures for solar panels can be installed in new and existing car parks. While the cost of installation (and occasional maintenance) is higher than for shade solutions using fabrics, a ROI analysis can clarify when the investment will be amortised and the owner of the structure will begin generating income from sale/use of renewable energy. Today, solar car parks come in many shapes and forms in Sydney and globally (Figure 34).

However, it must be noted that currently commercially available PV technologies (mono and polycrystalline and amorphous silicon) convert only a small fraction of solar radiation into electricity and release the remaining solar energy into the urban environment as heat, potentially further contributing to urban overheating (Sailor et al., 2021). The electricity conversion averaged over daylight hours is close to 10% for most technologies, with peak efficiencies in the range between 15% and 22% for single crystal PV cells (CRC LCL, 2013). Most of the literature is in agreement on their contribution to increasing urban heat (Sailor et al., 2021) and one robust empirical study concluded that the average daily maximum air temperature at the PV array was 1.3°C warmer compared to a reference site where there were no PV panels installed (Broadbent et al., 2019).

The effect on urban overheating and the possible heat increase from PV installations compared to vegetated or highly reflective sites should be considered. However, using this technology in unshaded black asphalt car parks has clear cooling benefits. Surface temperatures will be lower under the panels, and at least 10% of the energy hitting the PV panels will be converted into renewable energy, leaving less energy to accelerate urban overheating. In the future, coupling of PV with reflective surfaces and/or green cover will deliver even greater cooling benefits and the new generations of photovoltaic cells are on track of improved conversion efficiencies (thus lowering the release of heat in the environment) but more research is still needed.

FIGURE 34: Examples of solar shade structuresover car parks. A: Sydney Markets in Flemington. Image © S. Pfautsch. B: Car park P3 at Sydney Olympic Park. Image (c) S. Pfautsch. C: Solar car park at Kingswood campus of the University of Western Sydney. Image (c) S. Pfautsch. D: a combination of shade fabric with photovoltaic panels at Google company (Li and Zanelli, 2021).

Solar panels deliver environmental benefits, with the most obvious being clean energy production. However, another advantage that may not be obvious will be the effect of shade on fuel consumption and the emission of greenhouse gases , particulate matter and heat from the exhaust pipe. As documented in Section 3.3 of this report, the shade created by solar panels can considerably cool surfaces of car parks and vehicles parked underneath. At the same time, shading the car's exterior also reduces interior temperature, positively affecting human thermal comfort and fuel consumption. When a vehicle is shaded, it will use less fuel to operate air conditioning that cools the temperature inside more efficiently than a car parked in full sun. By contrast, it may take up to 30 min for an unshaded vehicle to reach thermally comfortable conditions inside, which will be reflected in higher fuel consumption and thus increased pollution (Levinson et al., 2011).

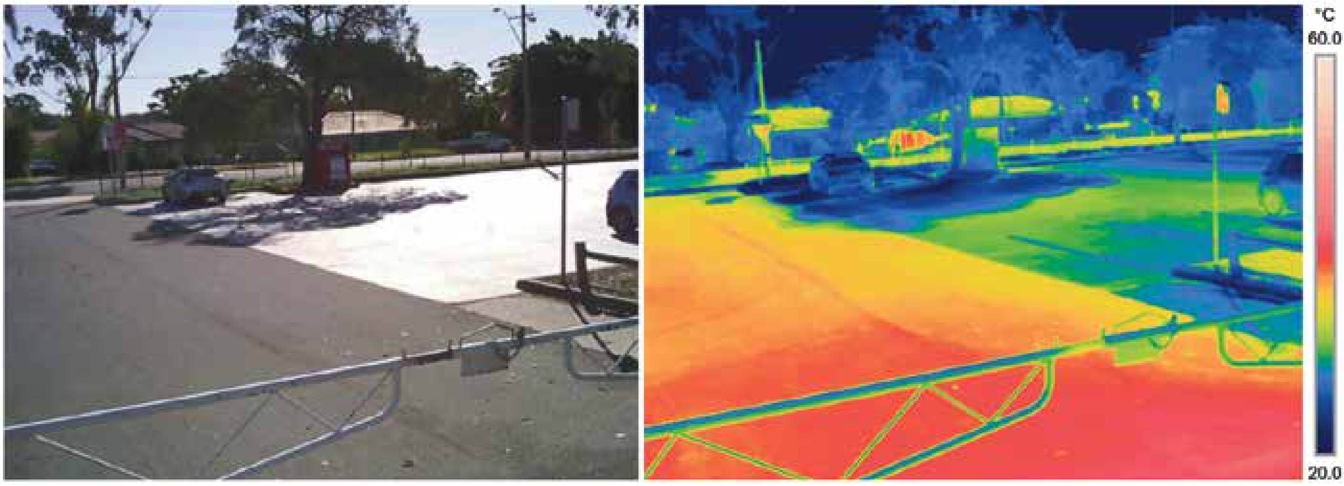


FIGURE 35: Normal and infrared images comparing unshaded coated and uncoated asphalt pavements at a car park in Old Toongabbie, western Sydney. The image was taken during the *Cool Roads Trial* at 15:40 on 18 April 2020. The scale on the right side indicates the range of surface temperatures represented by colour. The surface temperature of the uncoated car park in the sun (left) ranged from 38-44°C while the unshaded coated surface (right) had a surface temperature between 30°C and 33°C. Image © S. Pfautsch

5.3 **SURFACE COATING**

Pavements like asphalt have a low albedo and thus absorb large quantities of solar energy and reradiate this energy as sensible heat. This process leads to the warming of the surrounding environment during the day and night. Even during benign summer days, asphalt surfaces heated to 45°C, reducing human thermal comfort and warming ambient air (as shown in Sections 3.1 and 3.2). On extreme days, unshaded asphalt was nearly 70°C hot, further influencing the perception of temperature by car park users and with warming effects on the local area (as shown in Sections 3.2 and 3.3).

Coating unshaded pavement materials with highly reflective seal coats will increase surface albedo and reduce the absorption of solar energy. This in turn will minimise heat retention of the pavement material (Santamouris 2013; Cheela et al. 2021). This cooling effect was documented recently during the *Cool Roads Trial* across western Sydney (Pfautsch and Wujeska-Klause 2021a). The trial found that the applied seal coat reduced surface temperatures of unshaded asphalt by an average of 6°C, and occasionally up to 11°C (Figure 35). The range of the observed surface cooling effects was similar to other studies (6°C, Middel et al. 2020; 13°C, Cheela et al. 2021).

Points to consider when installing reflective seal coats:

- » The costs associated with the application on a large area like car parks.
- » The reflectivity declines over time because the paint degrades from exposure to UV radiation (Santamouris 2013; Cheela et al. 2021). The paint should be reapplied every 6-8 years to maintain its high reflectivity and low surface temperatures (Pfautsch and Wujeska-Klause 2021a). However, similar types of maintenance applications and costs can also be expected on conventional, uncoated asphalt surfaces.
- » Coated surface wears fast in high-traffic areas (Cheela et al. 2021), which decreases reflectivity and increases maintenance costs.
- » Selection of colour is crucial (Santamouris 2013; Cheela et al. 2021). Only light colours should be considered as they have a high albedo and thus surfaces would not store as much heat as dark-coloured materials. The effect of light and dark coats on concrete and asphalt was documented in several Western Sydney suburbs (Pfautsch and Wujeska-Klause 2021a).
- » Although seal coats effectively reduce surface temperatures (Santamouris 2013; Cheela et al. 2021), the application of highly reflective paint can lower human thermal comfort (Middel et al. 2020; Pfautsch and Wujeska-Klause 2021a). The temperature above the coated surfaces can be perceived as up to 3°C warmer than on uncoated materials (Pfautsch and Wujeska-Klause 2021a). To minimise the thermal effect on car park users, a seal coat is not recommended in areas with high pedestrian traffic.

Large-scale applications of the surface coating of residential streets and car parks have been done recently in Phoenix (Arizona) and Los Angeles (California). The City of Los Angeles has demonstrated that coating asphalt across entire suburbs can sufficiently lower surface heat island effects. The Streets LA unit has demonstrated this remarkable achievement using infrared images captured by the International Space Station (ECOSTRESS, land surface temperature of Los Angeles at 4 pm on 14 August 2021). The City of Los Angeles continues to apply highly reflective surface paints to mitigate the extreme and increasing summer heat.

Further, the visual comfort of pedestrians should be considered, with solar reflective pavements in the range between 25% and 30% delivering visual comfort similar to natural grass (Rosso et al., 2016). Also pavements reflecting in the near-infrared (invisible) portion of the solar spectrum (e.g., red pavement coatings such as those used for bus lanes) do not cause glare. In fact, glare issues are common at low solar angles (i.e., sunrise and sunset) on aged asphalt pavements when the aggregates are exposed, not being fully covered anymore by bitumen.

Cool coloured (i.e., near-infrared reflective) pavements can easily achieve solar reflectances in the range between 30% and 40% of solar reflectance, also with low reflectances in the visible range (Carnielo and Zinzi, 2013).

5.4 PERMEABLE SURFACE TYPES

Pervious pavement materials and products are a great alternative to heat-retaining impervious pavements. The thermal properties of some permeable surfaces were presented in this report (Sections 3.1 and 3.2), demonstrating cooler surface temperatures, improved human thermal comfort and lower nighttime air temperatures. Our empirical measurements match those of several modelling studies (Takebayashi and Moriyama, 2009; Onishi et al. 2010). These studies evaluated the theoretical cooling effect when asphalt in car parks is replaced with grass cover. Results clearly indicated that the use of permeable grass cover led to lower air temperatures in the adjacent urban environment.

Conventional impervious surfaces not only retain heat but also prevent the infiltration of water into the ground. The advantage of using permeable pavements is the ability of water to pass through the surface, which has a number of benefits, including replenishment of soil moisture and hydrological systems, reduction of water runoff/flooding and cooling of the material's surface (Scholz and Grabowiecki, 2007; Santamouris 2013; Roads and Maritime Services, 2017). Appendix 2 contains price estimates per m^2 for some of the permeable surfaces presented in this report.

The following permeable pavement materials can be used in car parks:

1. Porous asphalt or concrete. This material is a mixture of coarse aggregate with the primary material as the binder (Scholz and Grabowiecki, 2007; Santamouris 2013). These surfaces carry the weight of vehicles while allowing for good water infiltration. The infiltration capacity of porous asphalt and concrete is clearly visible in Figure 36.

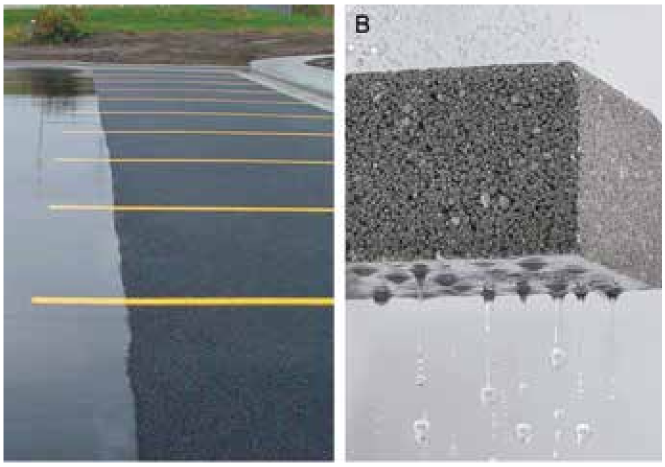


FIGURE 36: Examples of porous asphalt (A, Image © NAPA (2012)) and porous concrete (B, Image © hydrocon.com.au).

2. Recycled rubber mixed with gravel and a binder such as concrete or asphalt (e.g., Filter Pave, FiltaPave, MAISE Systems). These types of pavement materials can provide permeability, and may be a more environmentally friendly option compared to permeable asphalt or concrete due to re-using old tyres. The base material is blue metal or crushed aggregate with a compacted sub-base. This design has the capacity not only to capture and filter stormwater runoff but also to store it. However, given the high content of rubber material, it may retain heat on warm summer days, especially if the surface colour remains dark. Further, blockage of the porous spaces of these materials can be an issue. Figure 37 provides an example of recycled rubber surface used in a car park in western Sydney.

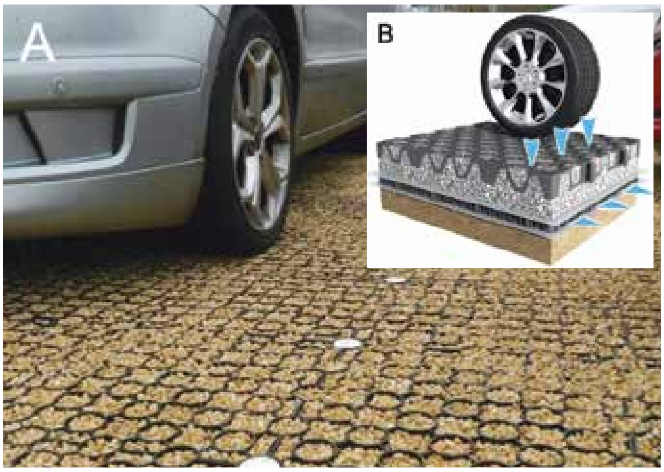
FIGURE 37: Example of recycled rubber mix used in a car park in Penrith, NSW. Image © FiltaPave (https://filtapave.com.au/)

3. Polyurethane resin mixed with aggregates (i.e., gravel). It can be applied directly into a porous material. Figure 38 depicts an example of the resin used in a car park at the University of Sydney (SuperStone™, MPS Paving Systems Australia). When using light-coloured aggregates, surface temperature and associated heat loads will be reduced further.

FIGURE 38: Example of resin mix (SuperStone™ from MPS Paving Systems Australia, www.mpspaving.com.au) applied to a car park at the University of Sydney. Image © SPEC-NET (www.spec-net.com.au).

4. Brick or concrete interlocking pavers. Light-coloured options should be preferred over darker colours to reduce the absorption of solar energy and storage and remission of sensible heat. As opposed to porous asphalt or concrete, the water infiltrates between the pavers rather than their surface. These materials can improve the surface strength of the car park. Costs for repairs are low due to access to individual pavers (MCPC, 2015). Given the wide range of shapes and colours, various patterns and designs are possible (Shackel, 2010). Figure 39 shows interlocking pavers used on the entire car park (A) or restricted to parking bays (B).

FIGURE 39: Examples of interlocking permeable surfaces used in the car park in Barton (A) and Amaroo (B), ACT. Images © hydrocon.com.au.



5. Gravel and stone. The loose gravel is reinforced with interlocking panels made from plastic or concrete (Figure 40). This surface allows for water infiltration, requires minimal maintenance and can support the weight of heavy vehicles. Also, Figure 27 provided another example of a car park made of stone material, with locally sourced light-coloured crushed sandstone.

FIGURE 40: Examples of gravel in parking lots with plastic reinforcement of interlocking panels (A: Image © ABG; B: Image © Rainsmart Solutions).

6. Grass pavers. These pavement types are usually a combination of reinforced polyethylene mesh or concrete to provide a stable driving surface for vehicles, yet the open space in their structure is used to grow natural turf (Figure 41). They have a high water infiltration capacity (Volterrani et al. 2001), while grass provides additional cooling through transpiration. The acceptable weight load depends on the use of reinforcement structure (MCPC, 2015).

FIGURE 41: Examples of using grass in car parks. A: grass with concrete reinforcement in a car park at the Technical University of Denmark in Lyngby (Image © Thomas Oles). B and C: grass with different types of plastic mesh reinforcement (Images © All Stake Supply).

Points to consider when installing permeable surfaces:

- Permeable surfaces will be most effective in hot and humid regions because the effectiveness of evaporative cooling increases with temperature and rainfall availability (Santamouris 2013; Sharifi et al. 2021).
- The type of material used will depend on the size of the car park area and the weight of the vehicles. For instance, grass may be restricted to parking bays, while the rest of the car park space is covered with more robust materials to support high traffic or large vehicles.
- Although permeable materials are cooler than conventional car park surfaces, they can still retain heat on hot and extreme days. It is recommended to reduce paved areas and use grass/reinforced grass pavers where possible.
- When installing grass/reinforced grass pavers in car parks, additional irrigation might be necessary to maintain plant vigour during dry, hot summers. Additional maintenance (e.g., cutting) may be necessary to retain aesthetics and cooling capacity (Sharifi et al. 2021).
- A membrane should be installed between the void and the subgrade to minimise groundwater contamination (Scholz and Grabowiecki, 2007). However, permeable materials should not be introduced when groundwater is close to the surface (Shackel, 2010).
- The water infiltration can be reduced over time (~10 years) due to pore blockage (Scholz and Grabowiecki, 2007). Thus, occasional surface cleaning may be required, which involves additional costs. Permeable materials should not be used in areas prone to sludge deposits or tidal cycles (Shackel, 2010).
- The surface colour matters for heat retention. Light colours should be used to increase reflectivity and minimise the absorption of solar radiation, maintaining low surface temperatures.

5.5 WATER SENSITIVE URBAN DESIGN

Water Sensitive Urban Design (WSUD) is a planning and design approach that allows for the temporary retention and slow discharge of rainwater in urban landscapes (Coutts et al. 2012; Roads and Maritime Services, 2017). It is a semi-natural way of retrieving and reusing water at the source. This design incorporates vegetation (i.e., grasses, shrubs and trees), permeable materials and an overflow system. The main aim of WSUD is to minimise stormwater runoff, which is a serious issue in the built environment. This engineering approach delivers several benefits (Coutts et al. 2012; Roads and Maritime Services, 2017):

- Reduction of the amount of rainfall runoff from paved surfaces
- Retention of water for irrigation of vegetation, which in turn provides cooling through transpiration
- Filtration of pollutants, improving water quality and protecting flora and fauna in the catchment area.
- Mitigation of urban heat by preserving water in the area and increasing surface cooling and evapotranspiration.
- Improvement of thermal comfort for urban residents
- Provision of aesthetics, habitat and enhanced biodiversity

The large open and paved surfaces of car parks provide excellent opportunities for inclusion of a wide range of WSUD designs. Here we list the most common ones and admit that the list of WSUD solutions is continuously expanding.

RAIN GARDENS

A shallow vegetated cavity with natural, pervious surfaces (i.e., gravel, sand) to promote infiltration and collection of water from impervious surfaces (Sabbion, 2018). This design option slows the flow of surface runoff and temporarily retains this water (Melbourne Water, 2013; Office of Environment and Heritage, 2015; Roads and Maritime Services, 2017). It aims to reduce the speed and the amount of rainwater entering the sewage system (Sabbion, 2018), as a stand-alone infrastructure or in combination with bioswales. Figure 42 depicts an example for a rain garden at Sydney Olympic Park.

BIOSWALES

The same design principle as rain gardens but a narrow and long version of rain gardens with typically low-growing vegetation (Sabbion, 2018). The main aim of this infrastructure is to slow the surface runoff and direct water to the stormwater systems or rain gardens while allowing for partial infiltration on the way (Melbourne Water, 2013; MCPC, 2015; Roads and Maritime Services, 2017; Sabbion, 2018). Bioswales can be used as a divider for parking bays or at the edges of the car park.

FIGURE 42: Raingarden at Murray-Rose Avenue in Sydney Olympic Park. The sloping road surface allows draining stormwater straight into the vegetated area on the left side. Open curb stones allow water flow whilst holding back larger debris. Image © S. Pfautsch.

TREE PITS

The pits apply principles of WSUD at a small scale, with rainwater runoff diverted directly to trees (Melbourne Water, 2013). In car parks, urban trees are usually surrounded by paved surfaces that restrict water infiltration, while the pits retain stormwater that is used to passively irrigate trees. Excess water is diverted into conventional stormwater drainage systems (Figure 43). Once established, trees will shade the surfaces underneath, providing additional cooling. This design can be used in car parks where rain gardens and bioswales are not applicable due to restricted space. Similar to porous surfaces, tree pits can also clog up and regular maintenance to provide optimal water infiltration is recommended (Melbourne Water, 2013).

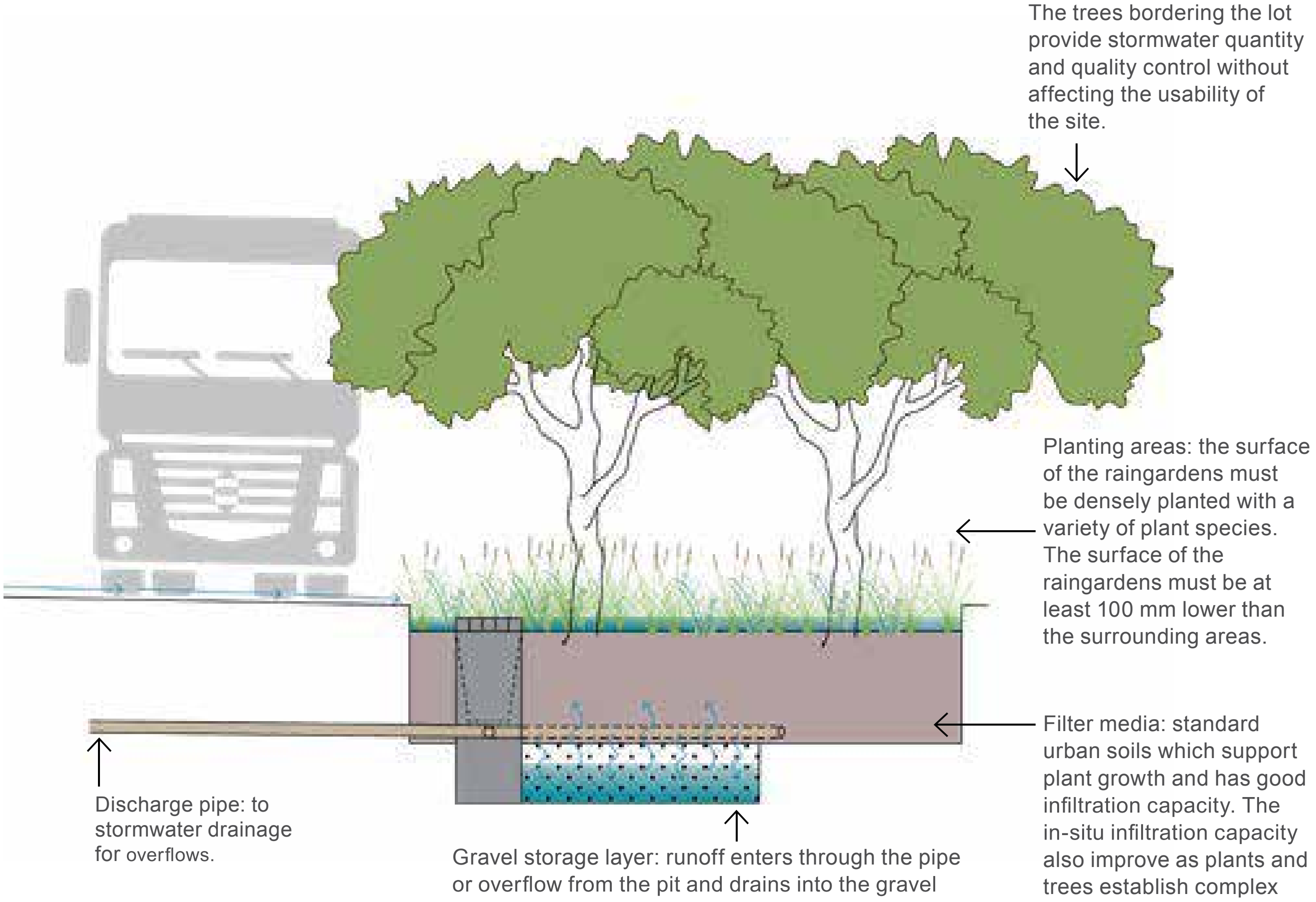


FIGURE 43: Example for an engineered solution of tree pits that aims to retain stormwater and slows the discharge of surface water into local waterways. Image © Sydney Water (2020).

Points to consider when implementing WSUD in car parks:

- Selection of plant species that are adapted to local climate conditions. Plant species need to be drought-tolerant, with the capacity to sustain periodic waterlogging (Office of Environment and Heritage, 2015).
- Calculating and planning for sufficient water intake capacity.
- Occasional maintenance and monitoring of vegetation. Watering may be required to help plants establish. Dense planting or mulching will suppress weeds, minimising maintenance (MCPC, 2015).

6. APPENDICES

APPENDIX 1

Standards, guidelines and other documents used in Section 4

Australian Building Codes Board (2020) National Construction Code, Volume 1. Building Code of Australia 2019 - Amendment 1. Australian Building Codes Board. 740p.

Blacktown Development Control Plan (2015) Part A - Introduction and General Guidelines. Blacktown City Council. 59p.

Liverpool Development Control Plan (2008) Part 1 - General Control for all Development. Liverpool City Council. Updated 1 February 2021. 157p.

NSW Government (year unknown) Car Parking Requirements in SEPP 65. Planning and Environment. 2p.

NSW Government (2017) Commuter Car Parks: Urban Design Guidelines, Interim issue.

Transport for NSW.

NSW Government (2017) Sustainable Design Guidelines (Version 3.0). Transport for NSW. 78p.

NSW Government (2019) Northwest Parking Management Strategy. Metro Sydney. 115p.

NSW Government (2020) Healthy Built Environment Checklist. NSW Ministry for Health. 160p.

Parramatta Development Control Plan (2011) Part 3 - Development Principles. Parramatta City Council. 85p.

Roads and Traffic Authority (2002) Guide to Traffic Generating Developments. Transport Planning Section, RTA. 172p.

Standards Australia (2004) Parking Facilities - Off-street car parking (AS2890.1:2004). 77p.

APPENDIX 2

Price estimates per m² for selected permeable materials presented in Section 5.4 of this report. The price does not include installation costs, as well as the price of grass or gravel filling.

Material	Cost (per m² or tonne)
Plastic reinforcement panels	~$AU21.50 - 42.00
Plastic reinforcement mesh	~$AU18.00 - 25.00
Concrete grass pavers	~$AU50.00 - 85.00
Interlocking concrete pavers (porous)	~$AU45.00 - 77.00 (light) ~$AU58.00 - 77.00 (dark)
Blue metal*	~$AU85.00

*price per ton

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