An uncoupled pavement-urban canyon model for heat islands

S. Sen
Graduate Research Assistant, Department of Civil and Environmental Engineering, University of Illinois at Urbana-Champaign

J.R. Roesler
Professor and Associate Head, Department of Civil and Environmental Engineering, University of Illinois at Urbana-Champaign

ABSTRACT: Urban Heat Islands (UHIs) are a major environmental consequence of developing urban infrastructure, including pavements. The effect of a specific pavement on the urban environment depends on not just the pavement structure, but also the weather and urban form of the location. To develop a rational approach towards incorporating these variables in UHI analysis, a microscale, uncoupled pavement-urban canyon model was developed and applied on the warmest hour for 30-year representative weather data in Chicago. The UHI intensity was found to vary spatially not just with the aspect ratio of the urban canyon, but also its relative position, as well as the structure of the pavement. Furthermore, future weather scenarios such as warming trends, elevated the UHI intensity.

1 INTRODUCTION

According to the World Bank, the proportion of people living in urban areas around the world is over 50% and continues to rise (The World Bank, 2015), with the proportion in the US being over 80%. Previous studies (Kleerekoper, van Esch & Salcedo, 2012, Oke, 1988, Oke, 1982, Aflaki et al., 2016, Santamouris, 2015) have investigated the energetics that lead to the development of UHI and have described the UHI intensity (ΔT_{ur}), the difference between the urban air temperature and adjoining rural area, as ranging from less than 1ºC to over 10ºC. In particular, the role of pavements in developing UHI through absorption and storage of solar radiation, and methods to mitigate the effect through reflective pavements, has received great attention (Antonaia et al., 2016, Qin, 2015, Santamouris, 2013, Yang, Wang & Kaloush, 2015, Sen & Roesler, 2016).

Pavement-induced UHI has been studied through a microscale approach that uses Computational Fluid Dynamics (CFD) to model the movement of heat through the urban environment (Declet-Barreto et al., 2013, Herbert, Johnson & Arnfield, 1998, Saneinejad et al., 2012, Taleghani, Sailor & Ban-Weiss, 2016, Toparlar et al., 2015). In particular, a few studies have also investigated the role of the urban canyon and its form on temperature distribution (Uehara et al., 2000, Xie et al., 2006). However, these studies have two shortcomings: they model the pavement as a single layer, typically a thin layer on top of soil; and they select an arbitrary "warm" day of a year, or arbitrary values of surface temperatures, for the analysis. Previous studies (Sen & Roesler, 2014, Gui et al., 2007) have shown that the thermophysical properties of pavements have an impact on their surface temperature, which should also be captured in microscale UHI modeling.

Current UHI studies focusing on outdoor temperatures, including the impact of pavements, only take into account the present weather conditions without considering the impact of possible future climate change. In the closely-linked area of building energy modeling however, a few studies (Crawley, 2008, Chan, 2011) have looked at developing future weather scenarios, mostly by modifying existing weather data through additive or multiplicative transformations. In particular, some studies (Du, Underwood & Edge, 2012, Eames, Kershaw & Coley, 2010) have used global future climatic simulations to estimate outdoor air temperatures in the UK, without focusing on pavements, which in turn was used to simulate building energy performance.

At the 2014 Pavement LCA Symposium, the authors showed (Sen & Roesler, 2014) how a set of pavement structures with varying surface and sub-surface thermophysical properties, simulated under the same weather conditions, showed different surface temperature distributions. This study follows up on that work to demonstrate a rational method to select a “warm” day for modeling UHI, and extends a pavement thermal model to act as a boundary condition for an urban CFD model for various urban forms for a single “warmest” hour of the year. Furthermore, it uses an additive approach to extend the analysis for future weather scenarious.

2 MATERIALS AND METHODOLOGY

2.1 *Scope*

The aim of this study was to analyze the effect of pavement structure, surrounding urban form, and climate change on the average air temperature at 2 m in an urban canyon, where human activity takes place. Four pavement structures are analyzed representing various changes to the pavement surface and sub-surface layers, which are discussed in Section 2.2. These were analyzed in three urban canyon configurations representing different urban forms, as discussed in Section 2.3. The far field weather data was representative of average conditions over 30 years, and was modified to simulate possible variations in the future, as discussed in Section 2.4. Finally, all these variables were analyzed using a 1D pavement heat transfer model as an uncoupled input to a CFD solver, as discussed in Section 2.5.

2.2 *Pavement Cases*

In this study, four pavement structures that were analyzed previously (Sen & Roesler, 2014) were considered. While details of the cases can be found in that paper, a brief summary is presented here:

a) <u>Case P:</u> This was a control case with a 100 mm thick concrete pavement of albedo 0.30 overlying a granular base of 150 mm, and a 300 mm granular subbase.
b) <u>Case PL:</u> This case was identical to the control case except that for the surface layer, lower-density concrete was used, which singifincatly lowered the density, thermal conductivity, and heat capacity of the layer.
c) <u>Case PT:</u> This case was identical to the control case except that the albedo of the surface was raised modestly to 0.35.
d) <u>Case PC:</u> In this case, the base layer of the control case was changed to a Cement Treated Base (CTB) to effectively change the thickness of the concrete surface layer from 100 mm to 250 mm.

2.3 *Urban Forms*

The urban canyon, which is essentially a road surrounded by buildings on both sides, is the fundamental repeating unit of a typical urban form, which can be studied in either 2D or 3D. Several studies (Pearlmutter, Berliner & Shaviv, 2006, Kruger, Pearlmutter & Rasia, 2010, Kondo et al., 2001) have shown that the shape of the urban canyon as well as its relative configuration are important parameters to take into account for urban CFD modeling. The urban canyon configuration adopted for this study is shown in Figure 1.

The fluid domain, which will be modeled in Figure 1, is shown with the definition of each boundary indicated. The urban canyon consists of a road of width W surrounded on both sides by buildings of height H, for an aspect ratio (AR) of H:W. Three identical buildings were assembled for this model. The width of the road was fixed at $W = 10\ m$, so the only free variable was H. The domain height was set at 20H and the wake length at 4H in accordance with best practice guidelines (Franke et al., 2007).

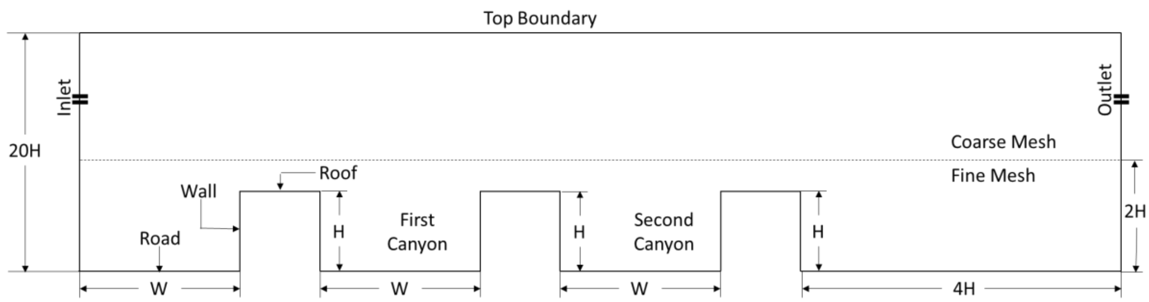

Figure 1. General urban canyon configuration with fluid domain.

In Figure 1, two canyons are marked as 'First Canyon' and 'Second Canyon'. The area to the left of the first canyon is used to allow the inlet wind profile to develop, and the area to the right of the second canyon is to allow for the development of a wake and to ensure that the outlet conditions do not affect the results. The top boundary is set at such a height as to ensure a 5% blockage ratio, as recommended. Three configurations were considered: $H{:}W = 0.5{:}1, 1{:}1,$ and $2{:}1$, by changing the height H progressively from 5 m to 20 m. The primary UHI metric of interest is the average air temperature at 2 m in the canyon, which represents the Canopy Layer UHI and the height impacting human health and activity.

2.4 *Far Field Weather Conditions*

In the CFD model, far field weather conditions have to be set as boundary conditions, which represent the general mesoscale conditions in the urban areas without regard to microscale variations. As discussed previously, the current practice is to select these conditions from meterological data for an arbitrary "warm" day of the year. As an alternative, a method was used to make a more rational selection and apply it to the "warmest" hour of the year, which can later extended to an entire day. Specifically, temperature and wind speed profile need to be specified. In this study, the Typical Meterological Year Series 3 (TMY3) was adopted, which uses weather data from 1961-1990 to construct a weather file (Hall et al., 1978) and, as the name suggests, represents a typical year in terms of weather conditions.

As an illustration, the TMY3 data for Chicago, Illinois (O'Hare International Airport) was extracted from the National Renewable Energy Laboratory (NREL, 2005), and the warmest hour in the database (which corresponded to July 19, 3:00 PM) in terms of dry bulb temperature, was used as the uniform inlet temperature profile boundary condition. This temperature was $T_0 = 35°\mathrm{C}$. The uniform inlet wind speed profile was set to a typical value of $U_0 = 2\ \mathrm{m/s}$ normal to the inlet boundary. For determining ΔT_{ur}, TMY3 data for an adjoining rural area is needed. However, the TMY3 data is maintained only for major airports in the region. Therefore, data from DuPage Airport, which lies about 60 km west of Chicago and represents a suburban area, was used. The corresponding dry bulb temperature for DuPage Airport was 31ºC for the warmest hour in Chicago (July 19, 3:00 PM). Thus, the mesoscale UHI intensity was 4ºC (35ºC -31ºC).

For this CFD models, three far field weather conditions were analyzed. The first used the TMY3 data with $T_0 = 35°\mathrm{C}$ for Chicago and 31ºC for DuPage, and this case was labeled 'TMY+0'. Then, the hourly dry bulb temperature was uniformly increased by 1℃ and 2℃ for 'TMY+1' and 'TMY+2' cases, for both Chicago and DuPage (thus, the mesocale UHI intenstity is kept constant at 4ºC). This additive increase in air temperature, which follows from the approach suggested by (Crawley, 2008), is used to simulate possible future changes in climate. This is a simplistic approach and a much more intensive climatological study would be required to obtain better future weather files but sufficent for this study. For the TMY+1 and TMY+2 cases, as in the TMY+0 case, the warmest hour was selected for analysis, for which $T_0 = 36°\mathrm{C}$ and $37°\mathrm{C}$ for Chicago and 32ºC and 33ºC for DuPage, respectively. The inlet wind speed was kept at $2\ \mathrm{m/s}$ for all cases.

2.5 *Analysis*

For each combination of pavement type, urban canyon form, and weather condition, two uncoupled analyses were conducted, as discussed next.

2.5.1 *1D Pavement Thermal Analysis*

A 1D pavement thermal analysis was performed on each combination of pavement case and weather conditions using a 1D heat transfer model, ILLITHERM (Sen and Roesler, 2016), developed by the authors. In this case, the weather conditions corresponded to the weather files generated from the TMY3 data and adjusted accordingly for the three far field weather condition cases, TMY+0, TMY+1, and TMY+2. In addition to weather data, the model also requires thermophysical properties of each pavement type, which can be found in (Sen and Roesler, 2014). From ILLITHERM, the pavement surface temperaure corresponding to the warmest hour in the TMY3 series was extracted and used as a boundary condition for the CFD analysis, as described next. Because the two modeling steps were performed separately, this approach can be described as an uncoupled pavement-urban canyon model.

2.5.2 *2D CFD Analysis*

The urban canyon geometry shown in Figure 1 was created using the commercial CFD software, ANSYS FLUENT (ANSYS, Inc., 2011). Before running a CFD simulation, a structured mesh was generated with elements of size 0.25 m below a height of 2H (marked as 'Fine Mesh' in Figure 1), and 5.0 m with an inflation factor of 10 above (marked as 'Coarse Mesh'). This mesh configuration balance the need for a fine resolution within the urban canyon with limitations to available computing capabilities, and was arrived at after a mesh convergence study. Mesh statistics revealed that the mesh was suitable for the simulation, and a cell size of 0.25 m was sufficiently fine for studying UHI at the Canopy Layer.

For the CFD analysis, the inlet boundary conditions were set as described in Section 2.4 and the road temperature was set as explained in Section 2.5.1. In order to isolate the effect of the pavement alone, the temperatures of the walls and roofs were set to be equal to the inlet condition T_0, although in reality, they too would vary like the road surface. A pressure condition was applied at the outlet with an operating pressure of 101,325 Pa (about 1 atm). Finally, the top boundary was set to a symmetry condition as per (Toparlar et al., 2015), although it was revealed in the mesh convergence study that this did not affect the average air temperature at 2 m in each canyon significantly.

The CFD analysis solved the complete Navier-Stokes Equations together with the Energy Equation as well as a turbulence closure model. A realizable $k - \epsilon$ turbulence model with standard wall functions was implemented for the solution. In order to prevent divergence, modest relaxation factors were used. As the Mach number anywhere in the domain was expected to be very small, a pressure-based steady state solver was used. Tolerances for scaled residuals were set at 10^{-3}, except for temperature, which was set at 10^{-6}, and the model was run to convergence.

3 RESULTS AND DISCUSSION

3.1 *Pavement Surface Temperatures*

The surface temperatures of each pavement case corresponding to the warmest hour in the TMY3 data were evaluated. A summary of the results is shown in Figure 2. Across the weather cases, TMY+0, TMY+1, and TMY+2, the far field air temperature was increased progressively by 1℃ from the baseline temperature obtained from the TMY3 weather data series. The corresponding surface temperatures obtained from ILLITHERM, interestingly, also increased by approximated the same amount, although the actual magnitude varied with the pavement structure. The low density concrete, Case PL, showed the highest surface temperature, while the more reflective case (PT) showed the lowest, and cases P and PC showed similar temperatures. As expected, all the surface temperatures were higher than the far field air temperature.

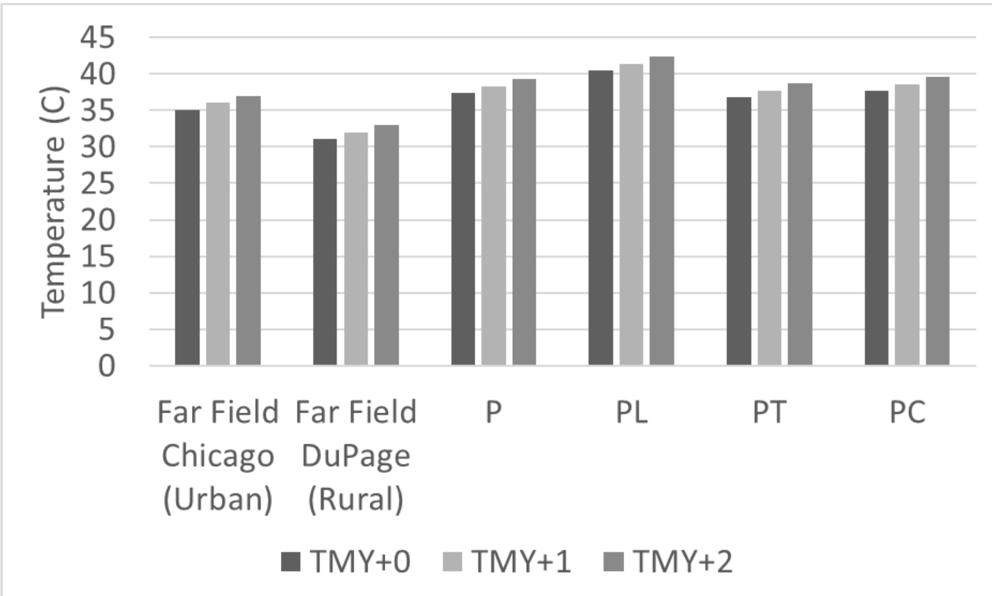

Figure 2. Pavement surface temperature in Chicago corresponding to the hour of maximum far field air temperature in Chicago and DuPage.

3.2 *Average Wind Speed at 2 m*

The velocity field inside the canyon is coupled with the temperature field through advection, which affects the average temperature at 2 m, and hence the UHI. This is a coupled process, as the temperature field affects the thermal stratification and hence velocity field in the canyon as well (Uehara et al., 2000). The study by (Xie et al., 2006) demonstrated that the urban canyon significantly decreases the wind speed from the far field value because of the formation of dissipative vortices, thus entrapping more heat inside. For the uncoupled pavement-urban canyon model, the average wind speed at 2 m in each canyon for a given AR was found to be more or less the same irrespective of the type of pavement under consideration. These wind speeds, normalized to U_0, are shown in Figure 3.

Figure 3 shows there is no significant change in the wind speeds across the three weather cases, given the inlet wind speed U_0 was assumed to be fixed at 2 m/s. The wind speed varies with the aspect ratio (AR), increasing as AR goes from 0.5:1 to 1:1 and then decreasing to 2:1. As the AR increases, the turbulence increases, which pushes the air into the canyon. However as AR further increases to 2:1, the velocity dissipates before it can reach to 2 m above the canyon floor (i.e., the road).

The relative position of the canyon affects the average wind speed and temperature at 2 m (see Figure 4). This can be seen in Figure 4 (c) in more detail by considering the wind velocity contours for AR 2:1, Case P, for TMY+2. The building before the first canyon causes the velocity field to be displaced upwards, which eventually falls back downwards. Depending on the height of the first canyon, this velocity field may or may not fall back into the second canyon. For AR 0.5:1 and 1:1, it does fall back into the second canyon, whereas it does not for AR 2:1, which explains the curves obtained in Figure 3. Furthermore, the wind speed and temperature distributions shown Figure 4(b) respectively, which indicates that even within a canyon at 2 m, there can be variation from point to point.

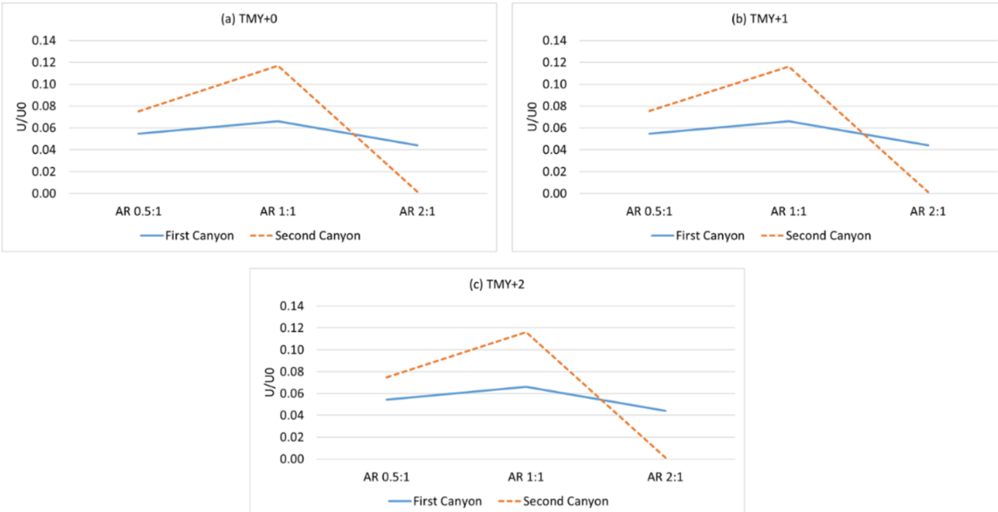

Figure 3. Normalized average wind speeds at 2 m for several aspect ratios (AR), H:W.

3.3 *UHI Intensity*

The average temperature at 2 m minus the far field air temperature in DuPage is a measure of the UHI intensity ΔT_{ur} in the corresponding canyon in Chicago. The uncoupled pavement-urban canyon model calculates the pavement temperature first, and then the temperature field in the canyon, from where the average temperature at 2 m can be extracted and ΔT_{ur} evaluated. Across all the cases, this is shown in Figure 5. For all the cases, for a given weather case and canyon form, the PL case shows the highest intensity, followed by cases PC, P, and PT. This correlates with the observations of surface temperature observed in Figure 2, indicating that in this uncoupled model, the air temperature strongly depends on the surface temperature. However, as can be seen in Figure 4(b), there is some variation in air temperature within the canyon even at 2m, which is not captured when using an average value.

Next, consider the behavior of the intensity with AR. In Canyon 1, the intensity decreases with AR, whereas in Canyon 2, it increases. This behavior results because of the formation of vortices in each canyon, as demonstrated for a single canyon (Xie et al., 2006), which advects the temperature field differently in each canyon. These vortices can be complex for a series of canyons like the geometry considered here, and the resultant behavior is difficult to predict. Therefore, even though the average wind speed shows the same trends with AR for both canyons (first increasing and then decreasing in Figure 3), the temperature fields don’t, as it depends on not just the magnitude but also the direction of the wind velocity.

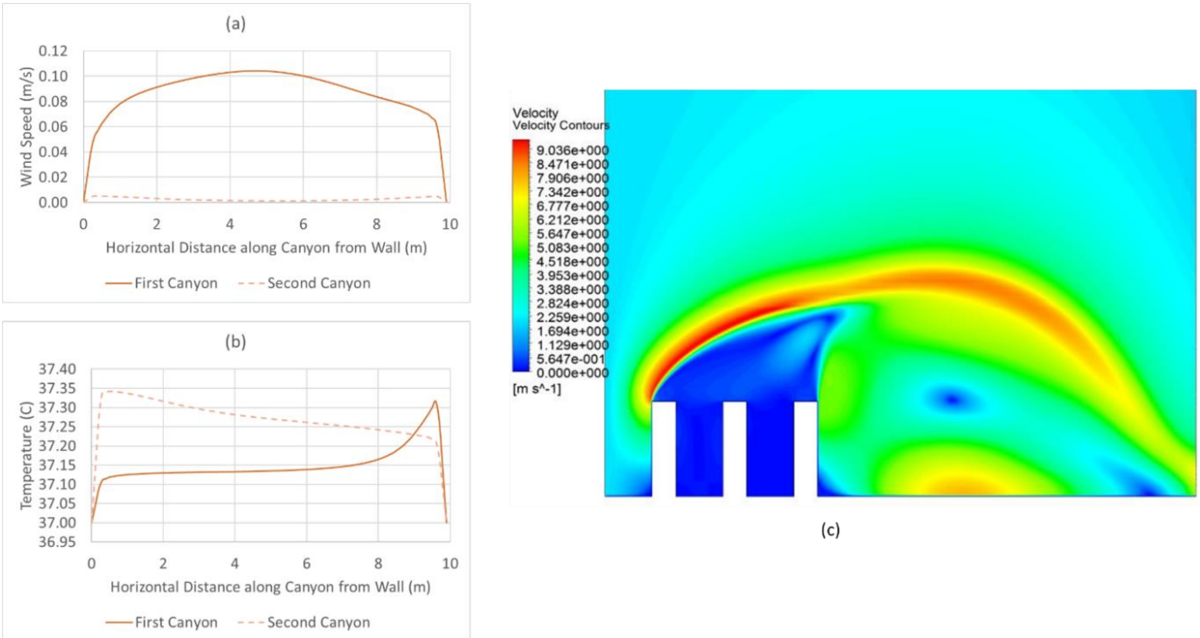

Figure 4. For pavement Case P and TMY+2 with AR 2:1, plots of (a) wind speed at 2 m (b) air temperatures at 2 m, and (c) contours of velocity magnitude

The UHI intensity for a given weather case and AR is the highest for the Case PL and lowest fo the case PT, with the magnitude varying from 4.1℃ to 4.6℃. The far field UHI intensity, which does not consider the effect of AR and the pavement, would be 4℃, across the weather cases. Thus, pavement type (both surface and sub-surface properties) also effects the local microscale UHI intensity. Finally, the UHI intensity does not seem to vary significantly with the increase in far field temperature in the TMY+0, TMY+1, and TMY+2 cases. However, in these cases, both the urban and rural temperatures were increased by the same magnitude. If the urban temperature increased more than the rural, the UHI intensity would have also increased. The actual differences between urban and rural temperatures in future climatic scenarios is however, not very well-studied and requires more research.

4 CONCLUSION

The urban environment can be complex because of the assortment of building forms and interaction between the wind velocity and air temperature fields, as well as the pavement structures found in a city. Uncertainty in future climate adds to the complexity. To rationally analyze these factors, representative weather data for 30 years in Chicago, the TMY3 series, and predicted future weather scenarios, were input into an uncoupled pavement-urban canyon model for a microscale, CFD-based UHI analysis. To account for the surface temperature of road in UHI analysis, a pavement thermal analysis was performed using four different pavement types, which varied both the surface and sub-surface physical properties. The urban canyon CFD model idealized various urban forms by changing the aspect ratio (AR) of the canyon. The analysis was performed for combinations of these variables given the warmest hour of the year represented by the TMY3 data. The CFD-based UHI model estimated the impact of the pavement type, urban form, and weather data on the average wind speed and air temperature at 2 m in the canyon, which was then compared to a rural air temperature to determine the UHI intensity at that warmest hour.

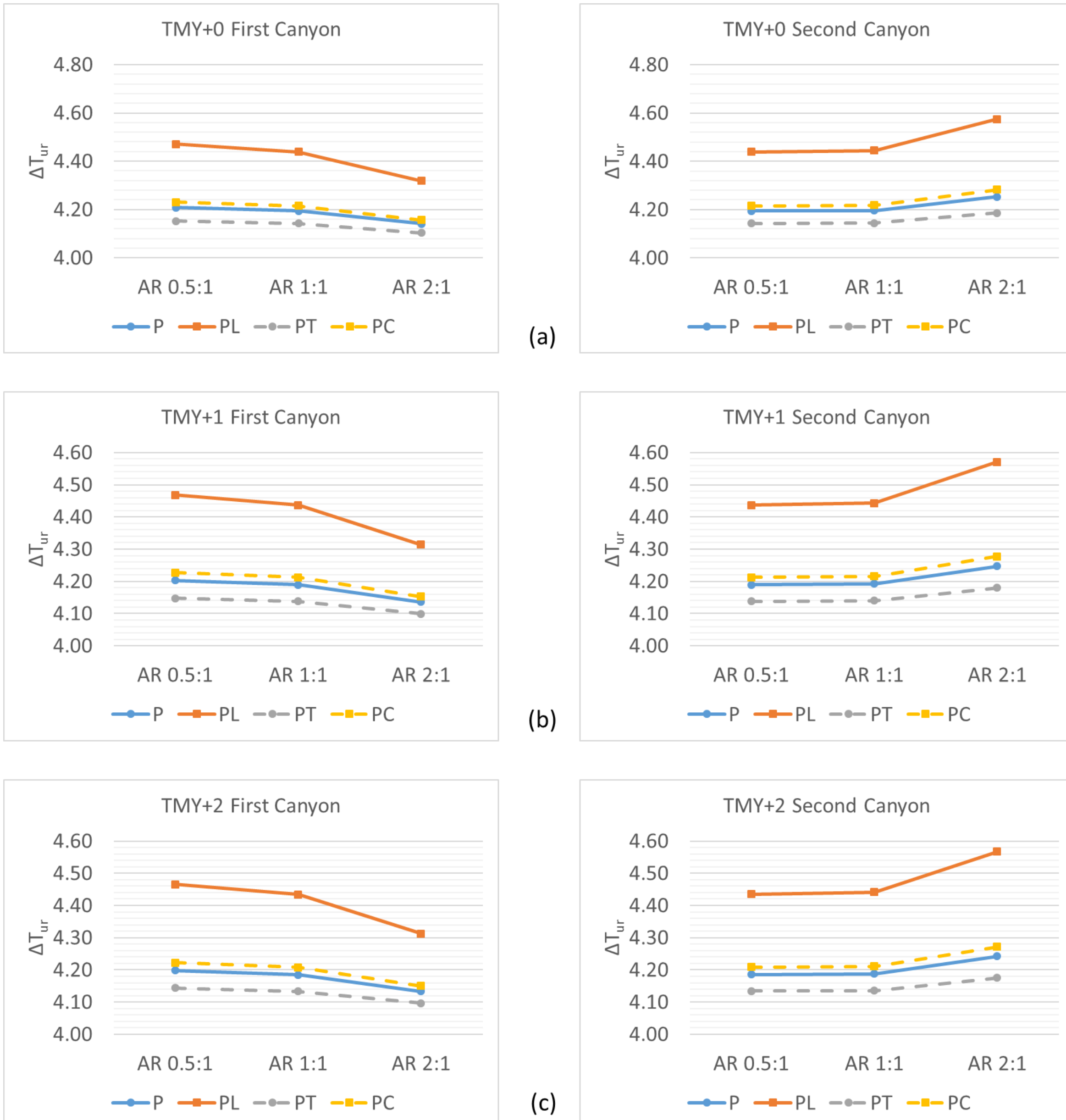

Figure 5. UHI intensity (in ºC) at 2 m for (a) TMY+0 (b) TMY+1 and (c) TMY+2 cases in Chicago relative to DuPage. Plots on the left are for the first canyon and those on the right for the second canyon.

For the TMY3 series at the warmest hour in Chicago, the difference in the 2m temperature between Chicago and rural Dupage is 4°C. As the far field air temperature increased in Chicago, both the pavement surface temperature and average air temperature at 2 m in an urban canyon increased. If the far field air temperature increases equally in both rural and urban areas, as modeled here, the UHI intensity is expected to remain the same. If however, it increases more for urban areas, the UHI intensity would also increase.

Next, the UHI intensity varies with the type of pavement. The intensity was highest for the Case PL, which uses lower density concrete on the surface, and lowest for Case PT, which is a more reflective concrete. The difference between these cases was about 0.5℃ on average, which is a significant difference for UHI intensity. The control pavement, Case P, and the Case PC, which had a CTB instead of a granular base, showed only a marginal difference between themselves for the hour analyzed.

Finally, the UHI intensity varied both with the aspect ratio of the urban canyon as well its position. In the First Canyon, the UHI intensity, ΔT_{ur}, was found to decrease with AR, whereas in the Second Canyon that was adjacent to the First, it was found to increase. The difference can be attributed to the development of complex vortices in the canyon and the resultant variation in wind velocity field in each. Prediction of this phenomenon can be quite complex without using microscale CFD.

The methodology proposed in this paper can be used for pavement engineers to work with communities, with unique urban forms and possible changes in future climate, to design better pavements and roadside features to mitigate UHI. In the future, the development of a coupled model to take into account convective and radiative heat transfer and shadowing is underway.

5 ACKNOWLEDGEMENTS

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