An uncoupled pavement-urban canyon model for heat islands

Sushobhan Sen & Jeffery Roesler
University of Illinois at Urbana-Champaign

Pavement Life Cycle Assessment Symposium 2017
University of Illinois at Urbana-Champaign
4/13/2017, Champaign, IL
Outline

• Introduction
• Pavement cases
• Meteorological cases & TMY
• Urban forms
• Results & Discussion
• Conclusion
Introduction

• Urban Heat Island (UHI) is a sustained temperature difference between urban and adjacent rural areas
  • UHI intensity: $\Delta T_{ur} = T_{urban} - T_{rural}$
  • Mesoscale definition (1 – 100 km length scales)
  • Microscale (< 1 km) variation within a city

• Can be measured at several heights, but most significant is canopy height (about 2.0 m above the ground)

• Challenges:
  • Finding the “right time” to model UHI
  • Incorporating pavement structure and properties

Sen & Roesler (2017)
We know each of these cases has a different surface temperature at a given hour (From Sen & Roesler, 2014 and Sen & Roesler, 2017)

<table>
<thead>
<tr>
<th>Layer</th>
<th>Dimensions</th>
<th>Case P (Control)</th>
<th>Case PL</th>
<th>Case PT</th>
<th>Case PC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface Course</td>
<td>100 mm</td>
<td>Concrete</td>
<td>Low-Density Concrete</td>
<td>TiO₂ Concrete</td>
<td>Concrete</td>
</tr>
<tr>
<td>Base Course</td>
<td>150 mm</td>
<td>Granular (A-2-4)</td>
<td>Granular (A-2-4)</td>
<td>Granular (A-2-4)</td>
<td>Cement-Treated Base</td>
</tr>
<tr>
<td>Subbase Course</td>
<td>300 mm</td>
<td>Granular (A-3)</td>
<td>Granular (A-3)</td>
<td>Granular (A-3)</td>
<td>Granular (A-3)</td>
</tr>
</tbody>
</table>
Typical Meteorological Year (TMY)

• Months that show least deviation in dry bulb air temperature from a 30-year average (1976 – 2005, TMY Series 3) – hourly data

• Obtained from the National Renewable Energy Lab (NREL), US DOE for 1020 locations

• Provides a climatological basis for selecting far field weather conditions

• Used extensively for building energy modeling, even required by law in some instances

Sen & Roesler (2017)
Location and Weather Cases

• Analysis for the warmest typical meteorological hour in Chicago, IL
  • July 19, 3:00 PM, base condition air temperature = 35°C
  • Assume low wind speed of 2 m/s (about 4.5 mph)
  • For comparison of UHI intensity: DuPage, IL (base condition air temperature = 31°C for a ‘mesoscale’ UHI intensity of 4°C)

Sen & Roesler (2017)
Domain & Urban Forms

- Canyon width (W) fixed at 10 m
- Canyon height (H) increased with aspect ratio (AR) $H:W = 0.5:1, 1:1, 2:1$ (so $H = 5, 10, \text{ and } 20 \text{ m}$)
Pavement Modeling

• 1D Pavement Thermal Model – ILLITHERM (Sen & Roesler, 2016)
  • Finite difference solution to the Fourier Heat Equation (stabilized layers) and Philip-de Vries coupled heat and moisture model (granular layers)
  • Surface boundary condition: Incoming + outgoing radiation, convection (Robin condition)
  • Subgrade boundary condition: Constant deep-soil temperature (Dirichlet condition)
  • Evaluates surface temperature, used as BC for CFD Model
Canopy Modeling

• 2D Finite Volume solution (0.25 m grid size in fine region, 5.0 m with inflation in coarse region) of the complete (Reynolds Average) Navier-Stokes (RANS) Equations + Energy Equation + $k - \epsilon$ turbulence closure model (buoyancy ignored)
  • Modeled using ANSYS FLUENT
• Inlet: Far field wind speed (2 m/s) and TMY temperature
• Outlet: Pressure outlet and TMY temperature
• Other walls: Symmetry condition (based on mesh convergence study), except canopy road (Dirichlet condition from pavement model) and buildings (‘turned off’)

Sen & Roesler (2017)
Research Approach

1D Pavement Thermal Model → Typical Meteorological Year → Urban Form

Uncoupled Models

Pavement Structure & Properties → CFD Canopy Model → Average Canopy Layer Temperature

Sen & Roesler (2017)
Results & Discussion
Surface Temperatures

Sen & Roesler (2017)
Typical Results

Sen & Roesler (2017)
Average Wind Speed at 2.0 m

Does not vary with far field temperature condition

Sen & Roesler (2017)
Temperatures (ºC): TMY+0

Sen & Roesler (2017)
Temperatures (ºC): TMY+1

Sen & Roesler (2017)
Temperatures (°C): TMY+2

Sen & Roesler (2017)
Discussion

• For all cases, $\Delta T_{ur}$ of PL > PC > P (control) > PT
  • Correlates with surface temperature
• Canyon 1: $\Delta T_{ur}$ decreases with AR
• Canyon 2: $\Delta T_{ur}$ increases with AR
• Increase in far field air temperature does not increase $\Delta T_{ur}$ - but still bad news!

Sen & Roesler (2017)
Conclusions

• Microscale UHI is influenced by heterogeneous urban form and materials
• Climate change can exacerbate UHI
• Questions for future research:
  • Will rural temperatures really increase as much as urban temperatures due to climate change?
  • How do different pavement types in the same city affect microscale UHI?
Acknowledgements

• Funding for this study was provided by the US Department of Transportation through the University Transportation Center for Highway Pavement Preservation at Michigan State University
Thank You

• Questions?