Sidewalk Surface Temperature Prediction App: Feasibility Assessment

ME321: Introduction to Heat Transfer

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Executive Summary

Many pet owners care about the safety and comfort of their pets, as such, they likely care if adverse weather conditions were to cause their pet bodily harm. Our team set out to create a program that would use historical weather data and location specific soil data to calculate the sidewalk temperature at two experimental locations (Bethlehem, PA and Las Vegas, NV). We made a simplified physical model to calculate the radiation, convection, and conduction heat flux entering and exiting the system to determine the sidewalk surface temperature. With this model we developed a MATLAB program that would then compile all the physical conditions and weather data to allow us to assess temperatures above the safety limit in addition to providing a proof of concept for the development of an app to expand on this idea.

Our findings show that within the 48 hours we observed, beginning at midnight on July 4th, 2024, there are stretches of several hours in each location where the sidewalk temperatures are so hot that they could potentially cause burns to paw pads in contact with the sidewalk surface. This implies that our system can definitively predict times in which sidewalk temperatures can exceed the maximum.

It also should be noted that our process only accounts for extremely hot sidewalk temperatures as being a potential hazard for pets and fails to account for other potential hazards such as extreme cold, severe weather conditions, or poor air quality. This being said, our promising predictive data can likely be expanded to include all weather conditions, locations, and display the sidewalk temperature at any given time on a simple, cell-phone app.

Lay Summary

The goal of this project is to design a proof of concept program that can be made into a smartphone app. The goal of which would be to display if sidewalk temperatures are hot enough to cause hazardous health and safety conditions for consumers' pets. Our program uses local soil conditions and historical weather data of a specified area to calculate an approximate expected sidewalk temperature over the course of 48 hours in two locations, Bethlehem, PA and Las Vegas, NV. Through our temperature monitoring model, we found that our program was able to determine temperatures during the 48 hour stretch that would be excessively hot to the point where such temperatures would be harmful to animals. For this program to be expanded into an accessible app, it would need to be expanded to include additional locations, weather conditions, and potentially phone notifications to warn pet owners of hazardous sidewalk conditions between a range of times.

Introduction

On hot days, dog owners often run into difficulty with their pets being unable to walk on hot sidewalks. As the sidewalk temperature increases, so does the risk of damage to the paws of these pets. Dog paw pads will burn once the temperature reaches values of 40 degrees Celcius, but there is not an easily accessible way for pet owners to check if the sidewalks in their local area have reached an unsafe temperature. Currently, there are tools that allow for the monitoring of sidewalk or concrete temperature, but these are largely done through sensors. Companies like Giatec[1] have sensors and software designed for temperature and strength monitoring for placed concrete, but they require expensive installation for a finite area. There are not widespread, fully developed methods for pet owners to ensure the safety of their pets in many locations. Walkable[2], for example, is a project currently under development aiming to create an app to monitor sidewalk temperatures for dog walkers. At this time, Walkable's app is in beta testing and is only capable of modeling the temperatures for Sacramento, CA, where the project was founded.

Our team set out to evaluate the practicality of an app that would use numerical methods to calculate sidewalk temperatures. In order to do this, we first constructed a MATLAB program that utilizes existing locational data to calculate sidewalk surface temperature over a 48 hour period. This data was then adjusted through the alteration of parameters that could be subject to inaccuracy; *if* the sidewalk temperature data varies greatly based on potential inaccuracies introduced, then an app using numerical methods for calculation is not feasible as a useful tool for dog walkers. However, if the surface temperatures are stable with slightly varying parameters, then the numerical methods are feasible for implementation into a functional app.

For an initial evaluation, we analyzed two locations: Bethlehem PA and Las Vegas NV for comparison. For our first location we chose Bethlehem, PA because that is where our team is based. Las Vegas, NV was chosen as the second location, because it has more extreme weather conditions that should lead to higher risk of sidewalk paw burns. Analysis of these two cities should give a sufficient range of data to evaluate the effectiveness of the methods used.

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[1] "SmartRock®: Concrete Temperature and Strength Maturity Sensor." *Giatec Scientific Inc.*, 19 Nov. 2024, www.giatecscientific.com/products/concrete-sensors/smartrock-maturity-meter/#:~:text=SmartRock%20allows%20for%20an%20easy,Monitor%20concrete%20temperature. Accessed 06 Dec. 2024.

[2] *Walkable*, www.walkableweather.com/. Accessed 06 Dec. 2024.

Methodology

1. Physical System

Our system is assumed to be a 1 meter by 1 meter stretch of concrete that is 14 centimeters thick on top of 1 meter of ground soil. We assumed that the temperatures cease to vary significantly after 1 meter in depth. The top surface of the concrete is exposed to the ambient air, wind, and solar radiation. We analyzed our system when exposed to historical weather conditions for a 48 hour period, from midnight on July 4th to midnight on July 6th in 2024. We selected two locations to analyze our system at, Bethlehem, PA and Las Vegas, NV. The properties of the concrete and soil were assumed to change a negligible amount within the temperature range of the medium. Therefore the properties were found at 300K. The same assumption could not be made for the air properties, and therefore the properties of air were interpolated in the range of 250K to 350K to fully encapsulate any potential air temperature our system experienced throughout the 48-hour period.

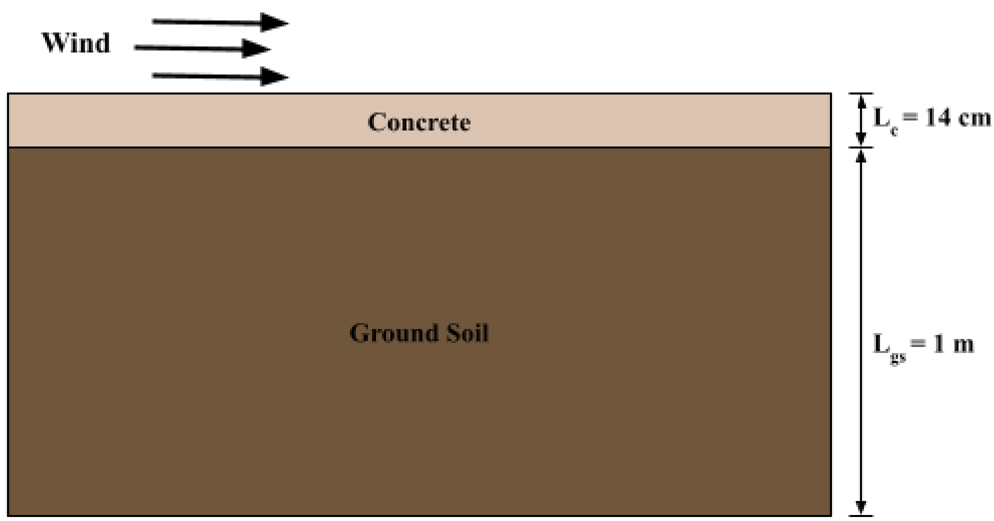

Figure 1: Proposed System Diagram

Using the the provided weather archive[3] we collected the weather data for our two locations over the time period of interest. We collected six data values from this website: the time at which each value was measured (hours), the temperature (°F), the humidity (%), the wind speed (mph), and the dew point (°F). We used the Bird Clear Sky Model[4] to calculate the irradiation values (W/m^2). Each of these values were put together into an excel table. The data was then cleaned and converted into proper units. Once read by the code, the ambient temperature, dew point temperature, wind speed, and irradiation data points were all then interpolated linearly from one hour to the next to yield a unique data point for each time step.

[3] The Weather Company. "Historical Weather." *WUnderground*, 2014, https://www.wunderground.com/history. Accessed 20 11 2024.
[4] NREL. "Bird Clear Sky Model." NREL, 1981, https://www.nrel.gov/grid/solar-resource/clear-sky.html. Accessed 20 11 2024.

2. Radiation

Within this model, we observe radiative heat flux in two modes, sun irradiation into the system and emission of heat radiation from the hot concrete to the surrounding sky out of the system.

The following equations are from the report *A Computer Model to Predict the Surface Temperature and Time-of-Wetness of Concrete Pavements and Bridge Decks*[5]:

$$q''_{rad} = \alpha G - q''_{sky} \qquad \left[\frac{W}{m^2}\right] \qquad 2.1$$

Equation 2.1 is for the net flux of an opaque surface where α is the solar absorptivity of concrete, for which we used 0.65, and G is the global horizontal irradiation, which represents the amount of solar radiation incident on a surface horizontal to the ground. The value for G was sourced from the Bird Clear Sky Model[6] by inputting parameters including the location (in terms of latitude and longitude), the time zone, the air pressure, the ozone thickness, the total column water vapor, and the aerosol optical depth.

$$q''_{sky} = \sigma\varepsilon_{sky}(T^4_{concrete} - T^4_{sky}) \qquad \left[\frac{W}{m^2}\right] \qquad 2.2$$

Equation 2.2 gives the heat flux of the concrete to the sky where σ is the Stefan-Boltzmann constant ($5.669 * 10^{-8}\frac{W}{m^2 * K^4}$), ε_{sky} is the emissivity of the sky (given in equation 2.3), and $T_{concrete}$ is the surface temperature of the concrete.

$$\varepsilon_{sky} = 0.787 + 0.764 * ln(\frac{T_{dew}}{273K}) * F_{cloud} \qquad 2.3$$

Equation 2.3 gives the emissivity of the sky, where T_{dew} is the dew point in Kelvin and F_{cloud} is the cloud cover factor (given in equation 2.4).

$$F_{cloud} = 1.0 + 0.024N - 0.0035N^2 + 0.00028N^3 \qquad 2.4$$

Equation 2.4 gives the cloud cover factor where N is the "tenths cloud cover" between a range of 0.0 and 1.0. For our analysis, we assumed worst-case scenario conditions, which would result in 0 cloud cover and an F_{cloud} value of 1.

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[5] Bentz, Dale P. A Computer Model to Predict the Surface Temperature and Time-of-Wetness of Concrete Pavements and Bridge Decks. National Institute of Standards and Technology, 2000. NIST, https://www.nist.gov/publications/computer-model-predict-surface-temperature-and-time-wetness-concrete-pavements-and.

[6] NREL. "Bird Clear Sky Model." *NREL*, 1981, https://www.nrel.gov/grid/solar-resource/clear-sky.html. Accessed 20 11 2024.

3. Convection

The sidewalk surface is continuously exposed to the air, enabling convective heat transfer to occur. The convection between the air and the sidewalk is assumed to be equivalent to that of a flat plate.

By assuming a mix of free and forced conditions we utilized equation 3.1 (Equation 9.64[7])

$$Nu_{tot}^{\ n} = Nu_{forced}^{\ n} \pm Nu_{free}^{\ n} \tag{3.1}$$

With the Nu_{free} being added to the Nu_{forced} and an n of 4, both of which are due to forced and free convection being perpendicular to each other. The flows are assumed to be perpendicular due to the fact that forced flow will be occurring parallel to the surface as it is caused by wind and the free flow will be perpendicular to the surface as it is influenced by gravity. Equation 3.1 can then be manipulated to yield Nu_{tot} as seen in Equation 3.2.

$$Nu_{tot} = \sqrt[4]{Nu_{forced}^{\ 4} + \ Nu_{free}^{\ 4}} \tag{3.2}$$

Using the fact that $\overline{Nu} = \frac{\bar{h}x}{k_{fluid}}$

$$\bar{h}_{tot} = \sqrt[4]{\bar{h}_{forced}^{\ 4} + \bar{h}_{free}^{\ 4}} \qquad \left[\frac{W}{m^2 * K}\right] \tag{3.3}$$

Where $\bar{h}_{forced}$ is:

$$h_{conv} = 5.6 + 4.0 v_{wind} \qquad \text{for } v_{wind} \leq 5\ m/s$$
$$h_{conv} = 7.2 \times v_{wind}^{0.78} \qquad \text{for } v_{wind} > 5\ m/s \quad \text{[8]} \tag{3.4}$$

$\bar{h}_{free}$ can be solved using horizontal plate correlations and $\bar{h}_{free} = \frac{\overline{Nu} * k_{fluid}}{x}$, where $x = \frac{Area}{Perimeter} = \frac{L^2}{4L} = \frac{L}{4}$. The table below gives the relevant Nusselt number calculations for all possible flat plate free convection scenarios. Each scenario was considered and accounted for in our code.

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[7] Bergman, Theodore L., and Adrienne S. Lavine. Fundamentals of Heat and Mass Transfer. 8th ed., Wiley, 2017

[8] Bentz, Dale P. A Computer Model to Predict the Surface Temperature and Time-of-Wetness of Concrete Pavements and Bridge Decks. National Institute of Standards and Technology, 2000. NIST, https://www.nist.gov/publications/computer-model-predict-surface-temperature-and-time-wetness-concrete-pavements-and.

$T_s > T_\infty$ $\quad$ $\overline{Nu}_L = 0.54(Ra_L)^{\frac{1}{4}}$ $\quad$ $10^4 < Ra_L < 10^7$ $\quad$ 3.5

$T_s > T_\infty$ $\quad$ $\overline{Nu}_L = 0.15(Ra_L)^{\frac{1}{3}}$ $\quad$ $10^7 < Ra_L < 10^{11}$ $\quad$ 3.6

$T_s < T_\infty$ $\quad$ $\overline{Nu}_L = 0.52(Ra_L)^{\frac{1}{5}}$ $\quad$ $10^4 < Ra_L < 10^9$ $\quad$ 3.7

$$Ra_L = \frac{g\beta(T_{surface} - T_\infty)L^3}{\nu\alpha} \qquad 3.8$$

Equation 3.8 is for the Rayleigh number where g is gravitational acceleration ($9.81\frac{m}{s^2}$), β is the volumetric thermal expansion coefficient (given in Equation 3.9), L is the length of the surface (in this case 1m), ν is the viscosity of the working fluid (air), and α is the thermal diffusivity of the working fluid (air).

$$\beta = \frac{1}{T_f} \qquad \left[\frac{1}{K}\right] \qquad 3.9$$

Equation 3.9 is for the volumetric thermal expansion coefficient where T is the absolute temperature of the T_{film} (which is the average of the surface and ambient temperature).
We can then solve for $q"_{conv}$ by using the standard convection equation as follows:

$$q"_{conv} = \overline{h}_{tot}(T_{ambient} - T_{surface}) \qquad \left[\frac{W}{m^2}\right] \qquad 3.10$$

4. Surface Node

Calculations for surface node, being the representation of the surface of the exposed sidewalk:

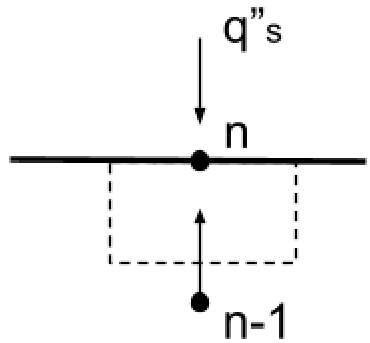

Figure 4: Surface Node

$$T_n^{P+1} = (1 - 2F_O)T_n^P + 2F_O T_{n-1}^P + 2F_O * \frac{q"_s * \Delta y}{k} \quad [K] \qquad 4.1$$

The $q"_s$ in the surface node is the total heat flux of the previous node, having the initial flux calculated separately at steady state conditions . This heat flux accounts for any heat stored by the concrete and soil. The temperature of T_n^{P+1} gives us the value we need to find the film temperature, which in turn allows us to determine air properties and heat flux values.

5. Conduction

For Bethlehem, PA we assumed that the soil consisted of equal parts wet gravel, wet sand, wet clay, and wet loam[9] and for Las Vegas, NV we assumed that the soil consisted of equal parts dry sand, dry gravel, and dry gravel[10]. These determinations of soil composition allow us to find its thermal conductivity, which is then used directly in the calculation of conductive heat flux. Using Table 1 we determined the average thermal conductivity of each location using the following equation: $k_{location} = \frac{\sum^{n} k_{rock\ type}}{n}$, where n is the number of rock types in the soil.

Rock Type	Thermal Conductivity (W/mK)			Volumetric Heat Capacity (MJ/m^{3}K)	Thermal Diffusivity (10^6 m^2/s)		
	Min	Typ	Max		Min	Typ	Max
Basalt	1.3	1.7	2.3	2.6	0.5	0.65	0.88
Greenstone	2	2.6	2.9	2.9	0.69	0.90	1
Gabbro	1.7	1.9	2.5	2.6	0.65	0.73	0.96
Granite	2.1	3.4	4.1	3	0.7	1.13	1.37
Peridotite	3.8	4	5.3	2.7	1.41	1.48	1.96
Gneiss	1.9	2.9	4	2.4	0.79	1.21	1.67
Marble	1.3	2.1	3.1	2	0.65	1.05	1.55
Mica schist	1.5	2	3.1	2.2	0.68	0.91	1.41
Shale sedimentary	1.5	2.1	2.1	2.5	0.6	0.84	0.84
Limestone	2.5	2.8	4	2.4	1.04	1.17	1.67
Loam	1.5	2.1	3.5	2.3	0.65	0.91	1.52
Quartzite	3.6	6	6.6	2.2	1.64	2.73	3
Salt	5.3	5.4	6.4	1.2	4.42	4.5	5.33
Sandstone	1.3	2.3	5.1	2.8	0.46	0.82	1.82
Siltstones and argillites	1.1	2.2	3.5	2.4	0.46	0.92	1.46
Dry gravel	0.4	0.4	0.5	1.6	0.25	0.25	0.31
Water saturated gravel	1.8	1.8	1.8	2.4	0.75	0.75	0.75
Dry sand	0.3	0.4	0.55	1.6	0.19	0.25	0.34
Water saturated sand	1.7	2.4	5	2.9	0.59	0.83	1.72
Dry clay/silt	0.4	0.5	1	1.6	0.25	0.31	0.62
Water saturated clay/silt	0.9	1.7	2.3	3.4	0.26	0.5	0.68
Peat	0.2	0.4	0.7	3.8	0.05	0.10	0.18

Table 1[11]: Thermal Conductivity of Types of Rock

With an average k established, we were then able determine total resistance throughout the concrete and soil via the following equations:

$$R" = \frac{L}{k} \qquad \left[\frac{K*m^2}{W}\right] \tag{5.1}$$

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[9] National Cooperative Soil Survey. "Las Vegas Series." *Soil Series*, 09 2015, https://soilseries.sc.egov.usda.gov/OSD_Docs/L/LAS_VEGAS.html. Accessed 20 11 2024.

[10] National Cooperative Soil Survey. "Bethlehem Series." *Soil Series*, 07 2009, https://soilseries.sc.egov.usda.gov/OSD_Docs/B/BETHLEHEM.html#:~:text=GEOGRAPHIC%20SETTING%3A%20Bethlehem%20soils%20occur,from%202%20to%2045%20percent. Accessed 20 11 2024.

[11] Marquez, Jose, et al. "Ground Thermal Diffusivity Calculation by Direct Soil Temperature Measurement. Application to very Low Enthalpy Geothermal Energy Systems." *Research Gate*, 2016, https://www.researchgate.net/publication/296477663_Ground_Thermal_Diffusivity_Calculation_by_Direct_Soil_Temperature_Measurement_Application_to_very_Low_Enthalpy_Geothermal_Energy_Systems. Accessed 20 11 2024.

$$R''_{tot,cond} = R''_{concrete} + R''_{ground\,soil} + R''_{contact} \qquad \left[\frac{K*m^2}{W}\right] \qquad 5.2$$

$$q''_{cond} = \frac{T_{sur} - T_{ground}}{R''_{tot,cond}} \qquad \left[\frac{W}{m^2}\right] \qquad 5.3$$

These calculations were done to calculate the initial interior temperatures of the soil and concrete. The next equations discuss the time marching equations used to calculate interior temperatures after the initial start.

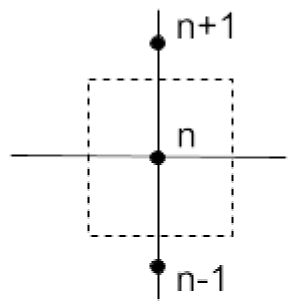

Figure 2: Interior Node

$$\alpha = \frac{k}{\rho c_p} \qquad \left[\frac{m^2}{s}\right] \qquad 5.1$$

The thermal diffusivity of the medium (α) is calculated by dividing the thermal conductivity (k, $\frac{W}{mK}$) by the density (ρ,$\frac{kg}{m^3}$) and the specific heat at constant pressure (c_p,$\frac{J}{kgK}$).

$$F_O = \frac{\alpha \Delta t}{(\Delta y)^2} \qquad 5.2$$

The Fourier's number (F_O, unitless) is calculated by multiplying the thermal diffusivity by a set time step and then divided by the nodal height step. Where the maximum time step can be determined by setting F_o equal to 0.5 and solving for the time step.

With Fourier's number calculated, the time marching equation can then be solved for.

$$T_n^{P+1} = F_O(T_{n+1}^P + T_{n-1}^P) + (1 - 2F_O)T_n^P \qquad [K] \qquad 5.3$$

Calculations for Boundary Nodes:

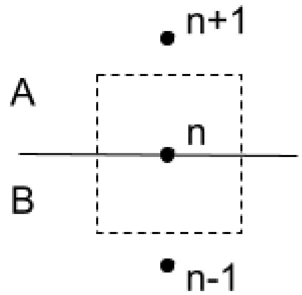

Figure 3: Boundary Node

$$F_{OA} = \frac{2k_A \Delta t}{(\rho_A c_{pA} + \rho_B c_{pB})(\Delta y)^2} \qquad 5.4$$

$$F_{OB} = \frac{2k_B \Delta t}{(\rho_A c_{pA} + \rho_B c_{pB})(\Delta y)^2} \qquad 5.5$$

$$T_n^{P+1} = F_{OA} T_{n+1}^P + F_{OB} T_{n-1}^P + (1 - F_{OA} - F_{OB}) T_n^P \qquad [K] \qquad 5.6$$

6. Total Heat Flux

$$q"_{total} = q"_{rad} - q"_{conduction} - q"_{convection} \qquad \left[\frac{W}{m^2}\right] \qquad 6.1$$

Equation 6.1 calculates the total heat flux for the system. Due to the way our equations were set up, the heat flux for conduction and convection were assumed to be leaving the surface node, while the radiative heat flux was entering the system. In the code, the convection heat flux will either enter or exit the system depending on if the ambient temperature is greater than the temperature of the concrete. The radiative heat flux of the sky will act similarly in that the concrete will either emit or absorb radiation from the sky depending on which has the higher temperature.

7. Properties Table

[K]	[kg/m^3]	[kJ/kgK]	[N*s/m^2]	[m^2/s]	[W/m*K]	[m^2/s]	[ ]
T	ρ	cp	μ * 10^7	ν * 10^6	k * 10^3	α * 10^6	Pr
100	3.556	1.032	71.1	2	9.34	2.54	0.786
150	2.336	1.012	103.4	4.426	13.8	5.84	0.758
200	1.746	1.007	132.5	7.59	18.1	10.3	0.737
250	1.395	1.006	159.6	11.44	22.3	15.9	0.72
300	1.161	1.007	184.6	15.89	26.3	22.5	0.707
350	0.995	1.009	208.2	20.92	30	29.9	0.7
400	0.871	1.014	230.1	26.41	33.8	38.3	0.69
450	0.774	1.021	250.7	32.39	37.3	47.2	0.686
500	0.696	1.03	270.1	38.79	40.7	56.7	0.684
550	0.633	1.04	288.4	45.57	43.9	66.7	0.683
600	0.58	1.051	305.8	52.69	46.9	76.9	0.685
650	0.536	1.063	322.5	60.21	49.7	87.3	0.69
700	0.498	1.075	338.8	68.1	52.4	98	0.695
750	0.464	1.087	354.6	76.37	54.9	109	0.702
800	0.435	1.099	369.8	84.93	57.3	120	0.709
850	0.41	1.11	384.3	93.8	59.6	131	0.716
900	0.387	1.121	398.1	102.9	62	143	0.72
950	0.367	1.131	411.3	112.2	64.3	155	0.723
1000	0.348	1.141	424.4	121.9	66.7	168	0.726
1100	0.317	1.159	449	141.8	71.5	195	0.728
1200	0.29	1.175	473	162.9	76.3	224	0.728
1300	0.268	1.189	496	185.1	82	257	0.719
1400	0.249	1.207	530	213	91	303	0.703
1500	0.232	1.23	557	240	100	350	0.685
1600	0.218	1.248	584	268	106	390	0.688
1700	0.205	1.267	611	298	113	435	0.685
1800	0.194	1.286	637	329	120	482	0.683
1900	0.183	1.307	663	362	128	534	0.677
2000	0.174	1.337	689	396	137	589	0.672
2100	0.166	1.372	715	431	147	646	0.667
2200	0.158	1.417	740	468	160	714	0.655
2300	0.151	1.478	766	506	175	783	0.647
2400	0.145	1.558	792	547	196	869	0.63
2500	0.139	1.665	818	589	222	960	0.613
3000	0.114	2.726	955	841	486	1570	0.536

Table 2[12]: Properties of Air at Select Temperatures

[K]	[kg/m^3]	[W/m*K]	[kJ/kgK]
T	ρ	k	cp
300	2300	1.4	880

Table 3[13]: Properties of Concrete at Constant Temperature

	[kg/m^3]	[W/m*K]	[kJ/kgK]	[kWh/(m^2)/day]
	ρ	k	cp	Avg Solar Radiation
Bethlehem, PA	2050	2	1840	6
Las Vegas, NV	2050	1.25	1840	7.9

Table 4[14] [15]: Properties of Soil at Constant Temperature

[12] Bergman, Theodore L., and Adrienne S. Lavine. Fundamentals of Heat and Mass Transfer. 8th ed., Wiley, 2017
[13] Bergman, Theodore L., and Adrienne S. Lavine. Fundamentals of Heat and Mass Transfer. 8th ed., Wiley, 2017
[14] Bergman, Theodore L., and Adrienne S. Lavine. Fundamentals of Heat and Mass Transfer. 8th ed., Wiley, 2017
[15] Marquez, Jose, et al. "Ground Thermal Diffusivity Calculation by Direct Soil Temperature Measurement. Application to very Low Enthalpy Geothermal Energy Systems." *Research Gate*, 2016, https://www.researchgate.net/publication/296477663_Ground_Thermal_Diffusivity_Calculation_by_Direct_Soil_Temperature_Measurement_Application_to_very_Low_Enthalpy_Geothermal_Energy_Systems. Accessed 20 11 2024. The average solar radiation for flat plate collectors at 0 degree angle in July is from NREL. "Bird Clear Sky Model." *NREL*, 1981, https://www.nrel.gov/grid/solar-resource/clear-sky.html. Accessed 20 11 2024.

Results

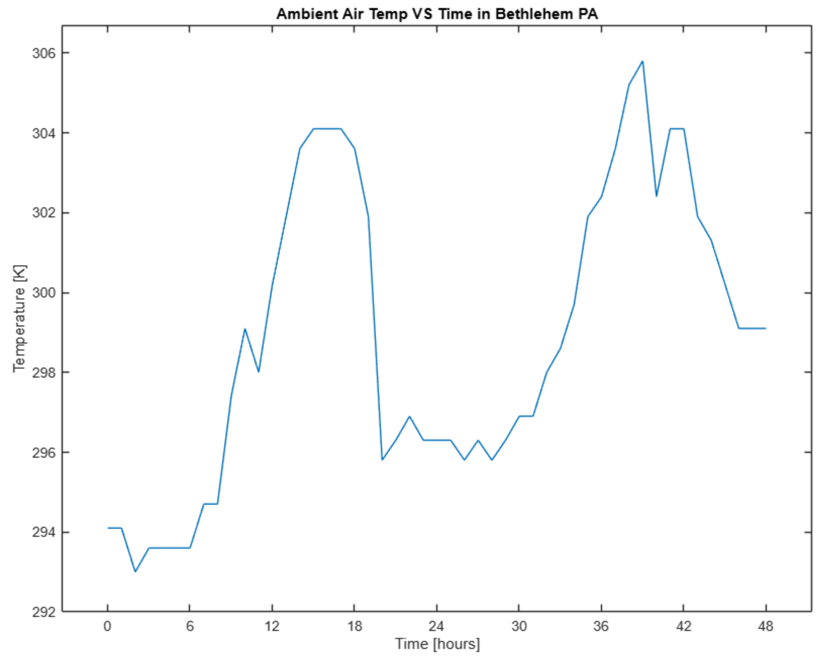

Figure 4: Ambient Air Temperature [K] vs Time [hr] for Bethlehem PA

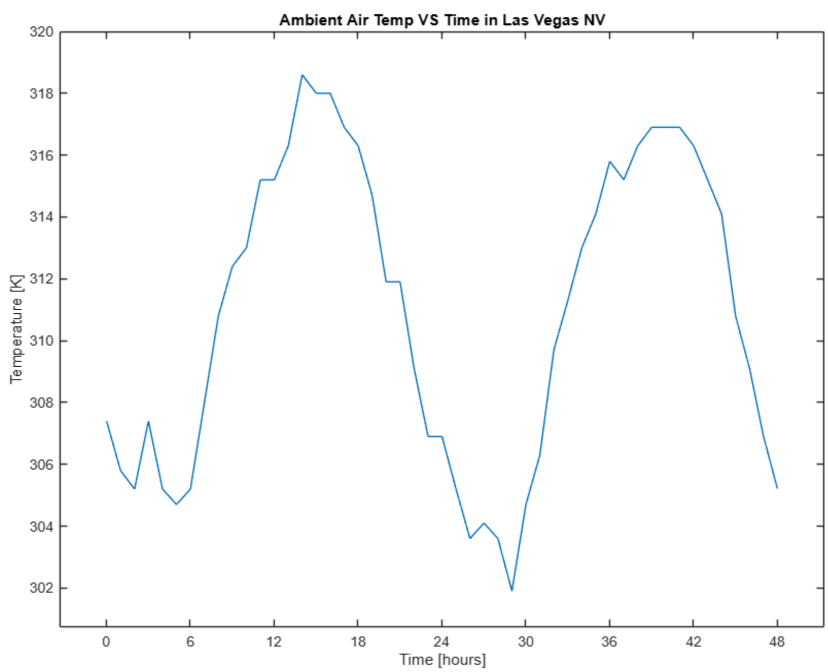

Figure 5: Ambient Air Temperature [K] vs Time [hr] for Las Vegas NV

From our code we were able to visually confirm our ambient weather data. As seen in Figure 4 and Figure 5, we can see that although Bethlehem PA and Las Vegas NV had different maximum and minimum temperatures, those peaks and valleys occurred at approximately the same time.

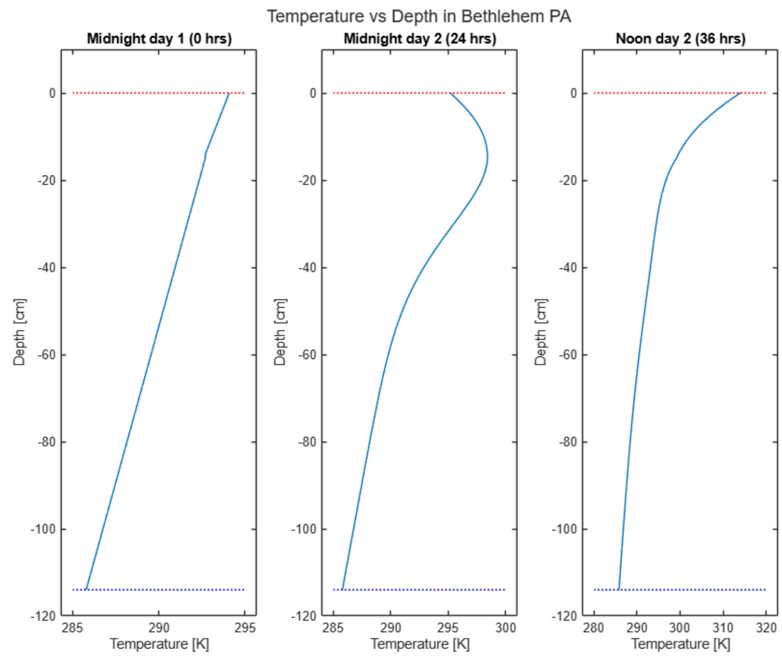

Figure 6: Temperature [K] vs Depth [cm] for Bethlehem, PA

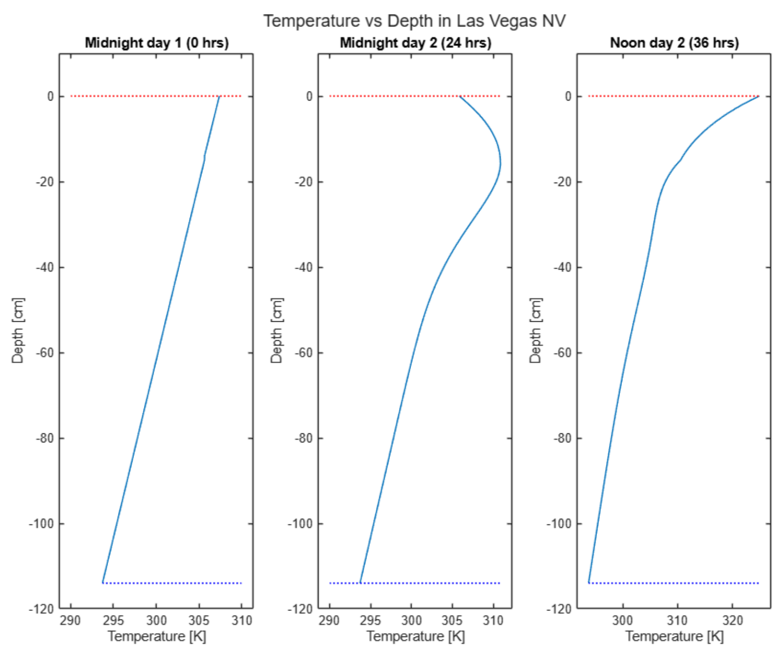

Figure 7: Temperature [K] vs Depth [cm] for Las Vegas NV

In Figure 6 and Figure 7, we see the lowest temperature for the three times displayed for both of the locations. Even though each location has different maximum and minimum temperatures for each depth, the trends of each temperature distribution at each time is the same. At midnight on July 4th and noon on July 5th for both locations the maximum temperature is at the surface of the concrete. At midnight on July 5th for Bethlehem PA the maximum temperature occurs at a depth of 15cm below the surface. At midnight on July 5th for Las Vegas NV the maximum temperature occurs at a depth of 16cm below the surface.

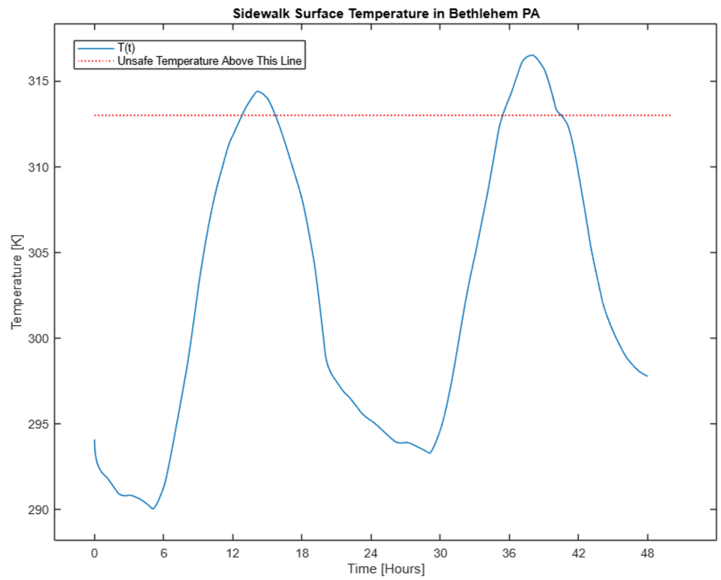

Figure 8: Sidewalk Surface Temperature [K] vs Time [hr] for Bethlehem PA

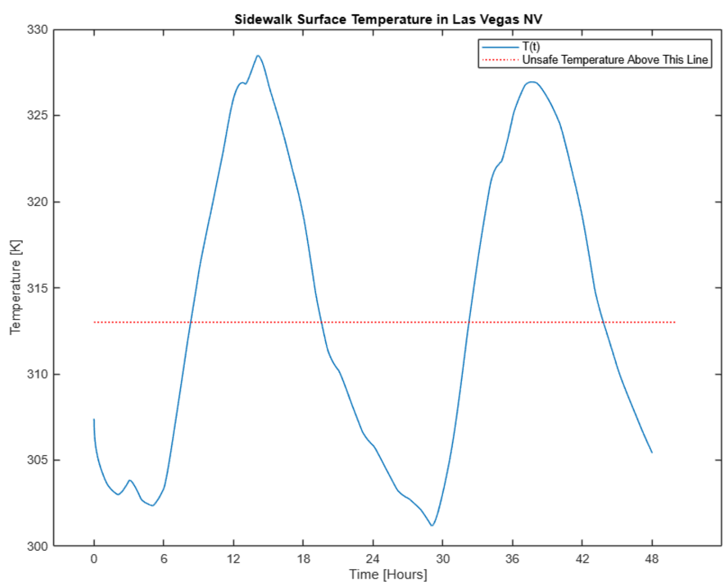

Figure 9: Sidewalk Surface Temperature [K] vs Time [hr] for Las Vegas NV

In Figure 8 and 9 the minimum sidewalk temperatures occur within the hour of 6am for both locations. The maximum temperatures of the sidewalk occur during or just before the hottest part of the day. Las Vegas, NV has more hours during the day that are above the unsafe pet walking temperature line than Bethlehem, PA. The curves of Temperature vs Time for both locations are smooth.

In order to evaluate the stability of these calculated values for real life circumstances, certain parameters previously assumed to be constant were varied. These parameters were chosen based on what values were most uncertain or likely to change from the initial calculations.

The contact resistance between the soil and the concrete slab was initially input as 0.00074 m2K/W, an experimentally determined value for densely packed sand and concrete[16]. Loosely packed sand and concrete has a higher contact resistance of 0.0102 m2K/W[17]. Changing the contact resistance in the calculation code did not cause a significant change in the sidewalk surface temperature. Variance in contact resistance for sidewalks will not undermine the accuracy of the calculated sidewalk temperatures.

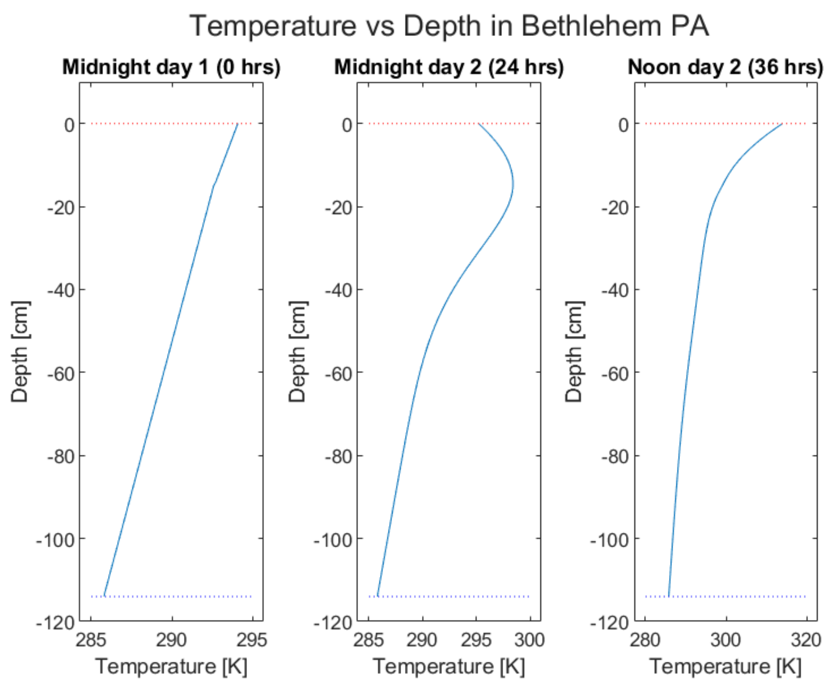

Figure 10: Temperature [K] vs Depth [cm] for Bethlehem, PA with modified contact resistance

[16] Figueira, João Diogo, et al. “A Novel Approach to the Evaluation of Contact Thermal Resistance at Soil-Structure Interfaces.” Instituto Superior Técnico, Universidade de Lisboa. https://doi.org/10.1051/e3sconf/202020506010

[17] Figueira, João Diogo, et al. “A Novel Approach to the Evaluation of Contact Thermal Resistance at Soil-Structure Interfaces.” Instituto Superior Técnico, Universidade de Lisboa. https://doi.org/10.1051/e3sconf/202020506010

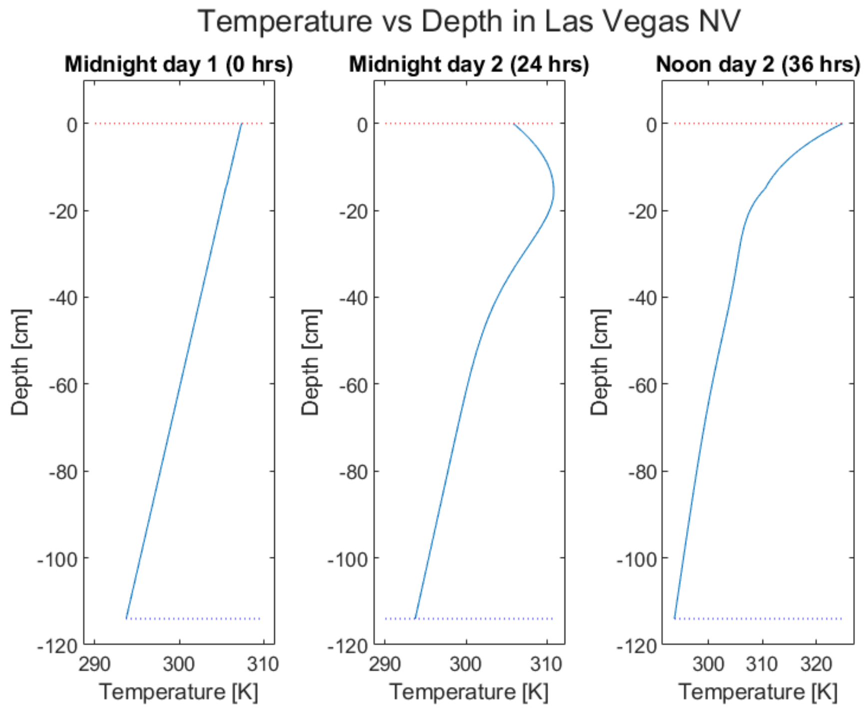

Figure 11: Temperature [K] vs Depth [cm] for Las Vegas NV with modified contact resistance

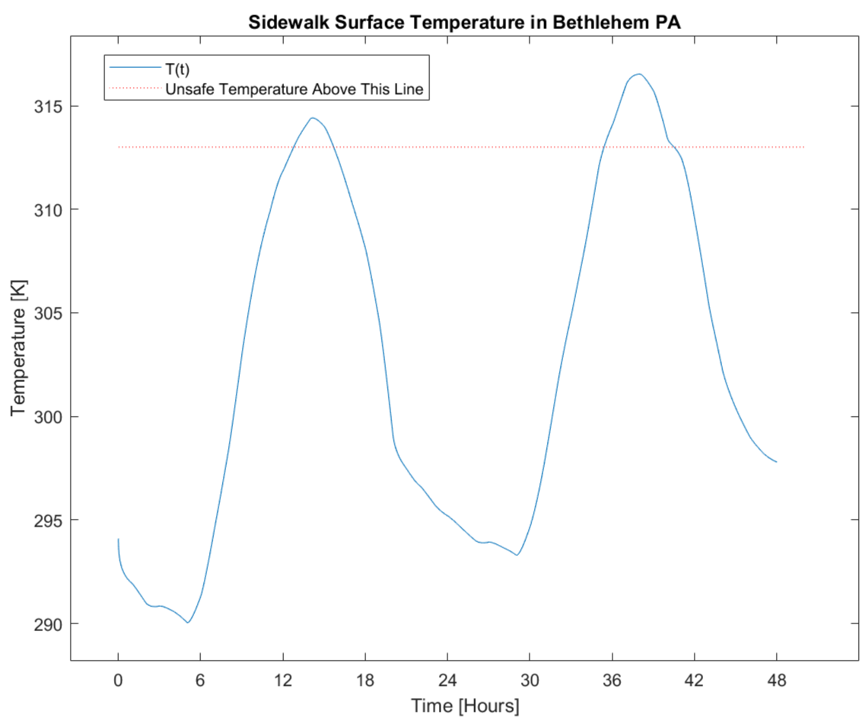

Figure 12: Sidewalk Surface Temperature [K] vs Time [hr] for Bethlehem PA with modified contact resistance

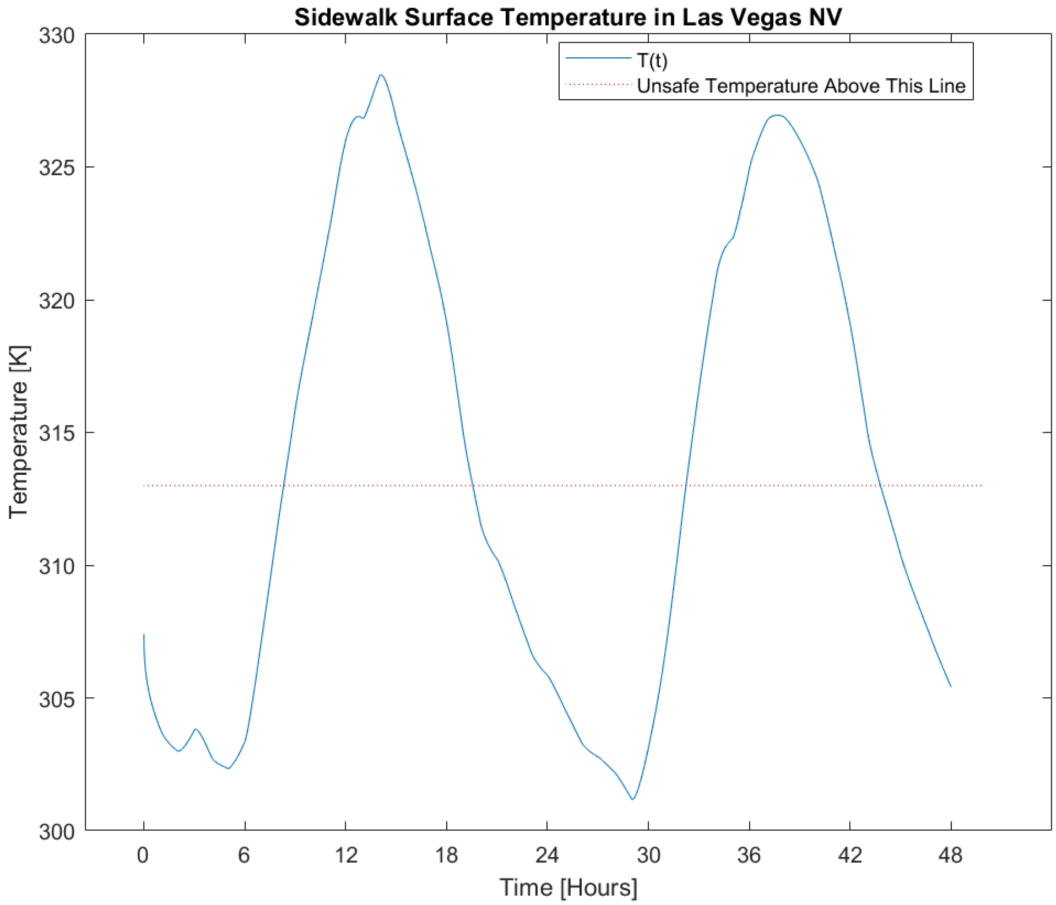

Figure 13: Sidewalk Surface Temperature [K] vs Time [hr] for Las Vegas NV with modified contact resistance

All calculations so far have assumed a 14 cm thick concrete slab for the sidewalks. Sidewalk thicknesses are not necessarily consistent. In warmer climates with less chance of damage due to freezing, sidewalks can be thinner. The Federal Highway Administration recommends a minimum thickness of 4 inches or 10.16 cm[18]. Assuming 10 cm thick sidewalks, there are minor changes in temperature distribution underneath the sidewalk surface but no significant change to the surface temperature.

[18] "A Guide for Maintaining Pedestrian Facilities for Enhanced Safety." *Federal Highway Administration*, safety.fhwa.dot.gov/ped_bike/tools_solve/fhwasa13037/chap6.cfm#:~:text=FHWA's%20Pedsafe%20Guide%20recommends%20a,inches%20for%20concrete%20slab%20depth.&text=Based%20on%20research%20conducted%20for,7%20inches%20at%20commercial%20driveways. Accessed 06 Dec. 2024.

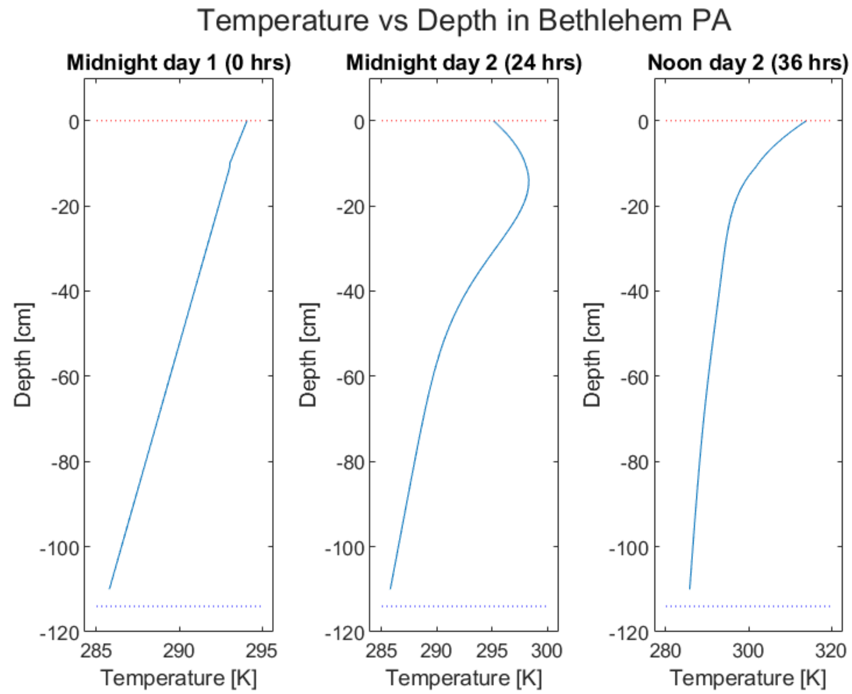

Figure 14: Temperature [K] vs Depth [cm] for Bethlehem, PA (10 cm sidewalks)

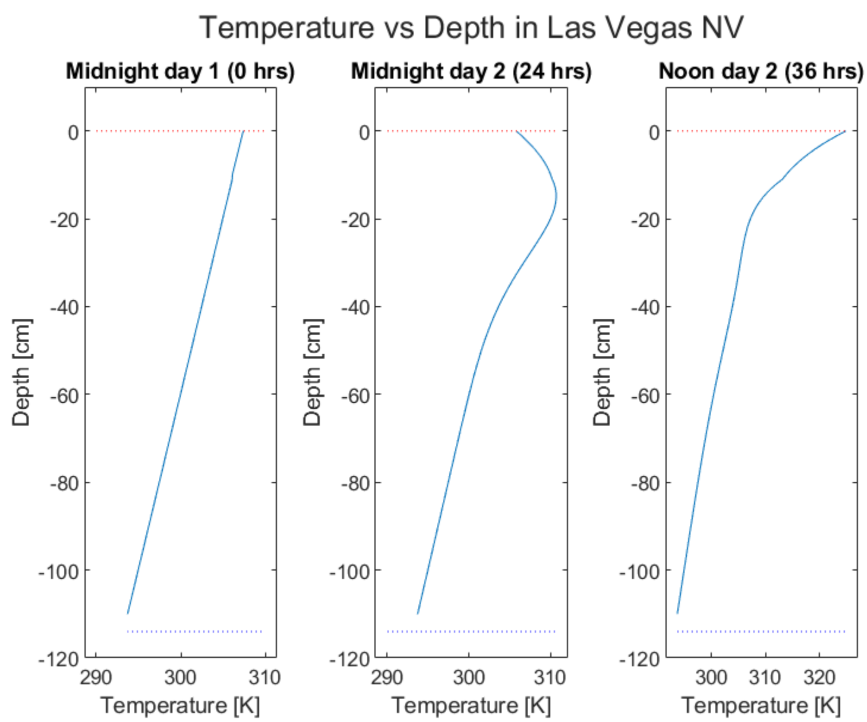

Figure 15: Temperature [K] vs Depth [cm] for Las Vegas NV (10 cm sidewalks)

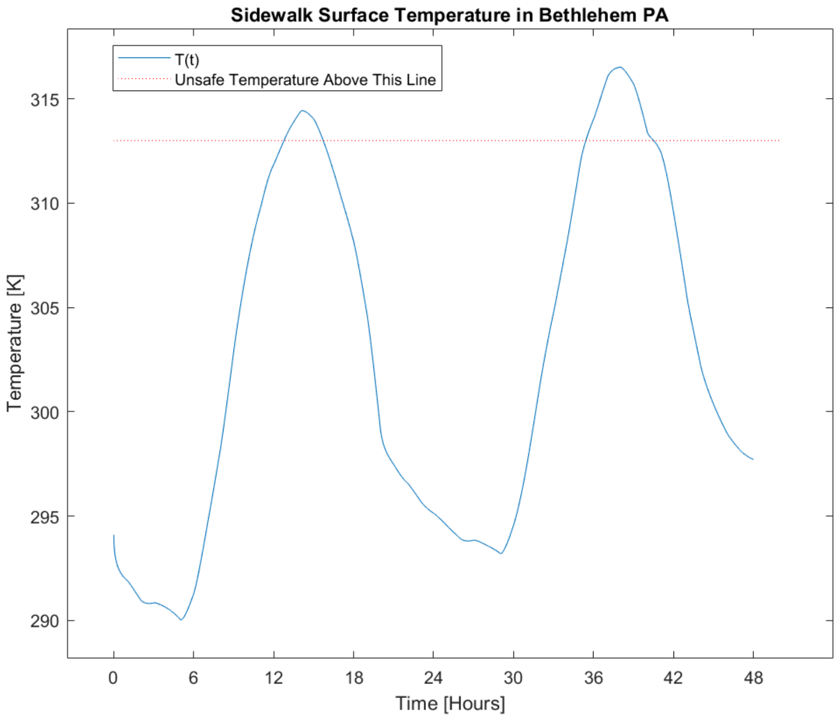

Figure 16: Sidewalk Surface Temperature [K] vs Time [hr] for Bethlehem PA (10 cm sidewalks)

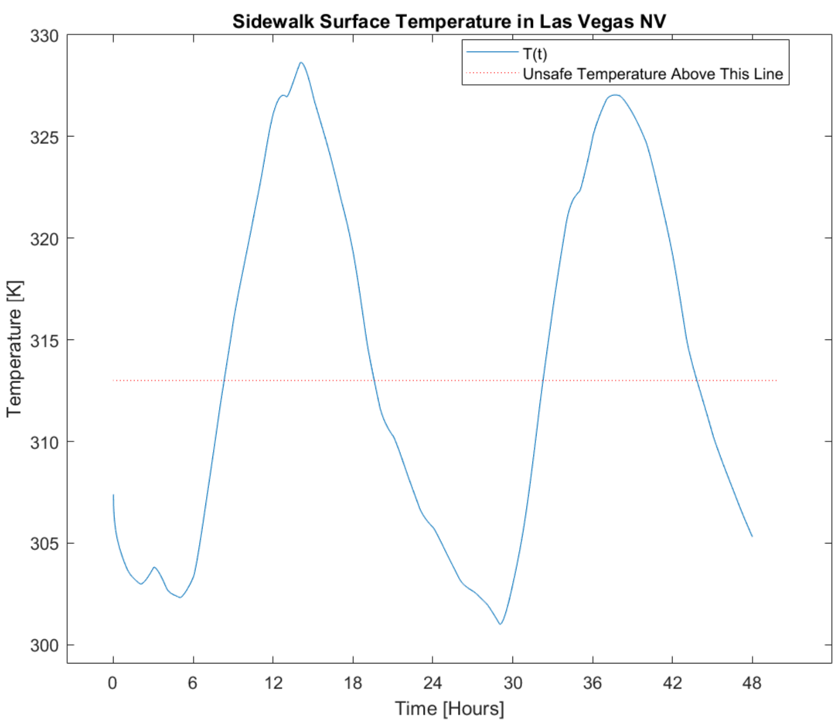

Figure 17: Sidewalk Surface Temperature [K] vs Time [hr] for Las Vegas NV (10 cm sidewalks)

Discussion

The temperature peaks of Figure 4 and Figure 5 across the two days corresponded with around 2-4pm each day. This matches with what we would expect in reality, because intuitively we know that the hottest part of the day is normally during the late afternoon. The temperature valleys of Figure 4 and Figure 5 across the two days corresponded with around 5-6am each day. Sunrise for Bethlehem PA and Las Vegas NV is around 5:30 AM for July 4th and July 5th 2024. This matches with what we would expect in reality, because intuitively we know that the coolest part of the day is normally during just after sunrise. The graphs for the ambient temperature in both of the locations have some jagged points, because we used linear interpolation to determine the values between each data point. If we were to use a spline prediction model to determine the values between data points, we anticipate that the graph would be smoother.

In Figure 6 and Figure 7 the location of the maximum temperature at midnight on July 4th is different from midnight on July 5th. We have data for the hours before midnight on July 5th, which allows us to account for the fact that the sidewalk has been cooling down since the sun set. We did not evaluate data for the temperature for the hours before midnight on July 4th. If the sidewalk were to keep cooling without ever heating back up, we anticipate that the parabolic shape in the nodes closest to the surface would begin to flatten until it reflects the leftmost graph. If no external heat was added to the sidewalk the whole system would cool down to the same temperature. The maximum temperature on midnight July 5th for both locations is below the concrete surface because there remains some heat that is stored under the sidewalk surface and in the ground. The relationship between temperature and ground depth for both locations at noon on July 5th is logarithmic because there is relatively little heat stored in the system yet, and so the hottest node will be the first and then it declines until it reaches the base soil temperature. The relationship between temperature and ground depth for both locations at midnight on July 5th is parabolic and linear because there is still stored heat being purged from the soil while simultaneously no radiation is entering the system.

In Figure 8 and 9 the minimum sidewalk temperatures occur on both days in both locations at 6am. This corresponds to just after when the coolest time ambient temperature of the day is recorded. This makes sense because concrete has a better heat retention than air, and so a lag is to be expected. The maximum temperatures of the sidewalk occur during or just before the hottest part of the day. This suggests that the impact of stored heat in the concrete coupled with increasing radiation contributions have greater influence over sidewalk temperature than the convection caused by wind and temperature differentials between the sidewalk surface and ambient air. Las Vegas, NV has more hours during the day that are above the unsafe pet walking temperature line than Bethlehem, PA. This is because the daylight temperatures of Las Vegas, NV get higher than the daylight temperatures of Bethlehem, PA. Additionally, Las Vegas, NV has an irradiance that peaks at a slightly higher value. Both locations have hours of the day where temperatures are so high that pets walking on sidewalks could potentially receive burns due to the extreme sidewalk temperature. The curves of Temperature vs Time for both locations are smooth because we have a gradient of ambient temperature between data points allowing us to more accurately calculate our sidewalk surface temperature at each time step.

Sidewalk surface temperature was shown to be largely unresponsive to reasonable variance in sidewalk thickness or contact resistance with the soil underneath. The ambient temperature, wind speed, and radiation were much more impactful on the data. The stability of the calculations means that we can have confidence in our numerical method as long as the input temperature, wind speed, and radiation data are reliable.

The model we used in this report was referencing tabulated data from the the past, so in order for the program to practically power an app the code would have to be adjusted. This would most likely be in the form of defining all of our operations with function handles without any specific inputs, and then values for ambient air temperature, wind speed, and radiation would be input constantly through data measured externally. This would require access to measuring equipment as well as a program to read these measurements into the MATLAB file. This would introduce new challenges but is feasible to accomplish, especially with the cooperation of local weather organizations for access to their data.

We assumed that the soil composition at each of our locations was uniform.There are many variables we did not account for in our analysis. We did not consider how mediums other than concrete would affect our calculations. Currently our code does not account for if it is raining or snowing. Our code also does not consider other unsafe conditions for pets, such as air quality or hazardous weather conditions.

This program, however, should be effective when it comes to determining a baseline approximation for the hottest parts of the sidewalk in direct sunlight with no cloud cover. Remaining sources of uncertainty (rain/precipitation, shade, etc.) would all result in cooler sidewalk temperatures under normal circumstances, and so while the code is not perfect it should succeed as a conservative model.

Conclusion

The purpose of this project is to determine if it would be feasible to create an app to predict the sidewalk temperature of a particular geographical location during a specific day of the year. This is done by gathering location specific data and historical weather conditions for a given location and then performing multiple heat transfer calculations in a MATLAB script to determine the sidewalk temperature for every hour. From this process our team was able to determine that there are multiple hours during the 48 hour time period after midnight on July 4th in both Bethlehem, PA and Las Vegas, NV that would be hot enough to cause pets walking on the sidewalk to receive burns due to the extreme temperatures.

While the code is not a perfect model, it is stable with slight variances in parameters like concrete depth and contact resistance. The model is reliant on a large amount of data for ambient temperature, wind speed, radiation, soil composition, and more. In order to have accurate calculations, there needs to be accurate data for the past to ensure the initial conditions are correct and must constantly take in new data to update the current sidewalk surface temperature. Our existing program used only data from the past, but new weather data is not immediately accessible in the form used in our program. It is important to note that if we were to make an app using these methods the app would require access to weather data inside of the MATLAB program as soon as that weather data is measured. Unless there is measuring equipment available, or a way to autonomously and constantly read data from weather websites into the program, the practicality of the app is dependent on cooperation of organizations that have access to measuring equipment for vital data such as temperature and wind speed.

The data acquisition is the largest challenge; our numerical methods are sound and our analysis shows that when fed the proper data this program is capable of forming a stable sidewalk temperature model. Our promising predictive data can likely be expanded to include all weather conditions, locations, and display the sidewalk temperature at any given time on a simple, cell-phone app. Our team believes that this app would be feasible to create if we had access to the necessary data.

Appendices

MATLAB Air Properties Interpolator

This code interpolates the Prandt number, viscosity, thermal conductivity, and thermal diffusivity of air at any given temperature, but for our purposes, we used film temperature. The initial air properties come from the property tables listed in Bergman, Theodore L., and Adrienne S. Lavine. Fundamentals of Heat and Mass Transfer. 8th ed., Wiley, 2017.

```
function [Pr,v,kf,a] = Interpolator(Tf)
airdata= csvread('AirTable.csv');
elnum=1;
  for i=(1:1:numel(airdata(:,1)))
     if Tf>airdata(i,1)
        elnum=elnum+1;
        Th=airdata(i+1,1);
        Tl=airdata(i,1);
     end
  end
  X=(Th-Tf)/(Tf-Tl);
  Pr=(airdata(elnum,8)+X*airdata(elnum-1,8))/(1+X);
  v=(airdata(elnum,5)+X*airdata(elnum-1,5))/(1+X)/10^6;
  kf=(airdata(elnum,6)+X*airdata(elnum-1,6))/(1+X)/10^3;
  a=(airdata(elnum,7)+X*airdata(elnum-1,7))/(1+X)/10^6;
end
```

MATLAB Sidewalk Temperature Prediction

This code uses the collection of constants and conditions we have collected over the course of this project and uses them to calculate an initial steady state reflection of our sidewalk system. Building off this screenshot in time, the code then proceeds to do similar calculations for total heat transfer throughout the system with the added process of calculating the nodal temperatures from the surface to a depth of 1.14 meters. This allows us to plot the surface temperature as a function of time as well as the temperature of each node as a function of position for any given time.

```
clc
clear
close all
%GIVENS
NodeStep=0.01;%meters
Lc=0.14;%meters
Lgs=1.00;%meters
EndTime=48;%hours
TsMAX=40;%degrees C (as given)
```

```
OneDay=24;%Hours
Length=1;%meter
%Constants
sigma=5.67*10^(-8);

Tgs0=[12.778+273 293.706];%Based on ground temp data
avg_Gs=[6 7.9];%kwh/(m^2)/day
Kgs=[2 1.45];%W/m*K
rho_gs=2050;%kg/m^3
cp_gs=1840;%J/kg*K
Kc=1.4;%W/m*K
rho_c=2300;%kg/m^3
cp_c=880;%J/kg*K
epsilon=0.9;
Rcontact=0.00074;%W/m*K
alpha=0.65;%place holder
%Time March Variable Definitions
    alpha_c=Kc/(rho_c*cp_c);
    dt=fix((NodeStep)^2/(2*alpha_c))/2;
    alpha_gs=Kgs/(rho_gs*cp_gs);
    Fo_c=alpha_c*dt/NodeStep^2;
    Fo_gs=alpha_gs*dt/NodeStep^2;

%Calculated Values
Rc=Lc/Kc; %R" of the concrete
%Initialization
Tset=zeros(int32((Lc+Lgs)/NodeStep+1),int32(EndTime/dt*3600));
depth=-(Lc+Lgs)/NodeStep:1:0;
NumLocations=2;
Tinfset=zeros(int32(EndTime/dt*3600),1);
%qtot=zeros(int32(EndTime/dt*3600),1);
location=["Bethlehem PA" "Las Vegas NV"];
%% BEGIN CALCULATION
for z=(1:1:2)% Loop for each location, z=1 is 18015 and z=2 is 87106
  %define constants based on z
  %Assumption: Ts @ t=0 is equal to Tinf
  if z==1 %PA
     data=readmatrix("BethlehemCond.txt");
  end
  if z==2 %AZ
     data=readmatrix("VegasCond.txt");
  end
  Tset(1,:)=Tgs0(z);
  Tset(end,1)=data(1,2);%T surface = Tinf @ t=0
```

```
%Initial Displays
%Abient Air Temperatures & Surface Heat Flux for 24 hours
Tinfsett=data(:,2);
Tinfset = interp1(1:EndTime+1,Tinfsett,1:1*dt/3600:EndTime+1-1*dt/3600,"linear");
figure(z)
nexttile
plot(1:1:EndTime*3600/dt,Tinfset(:));
axis([1  2400 0 inf])
xticks(0:6*3600/dt:EndTime*3600/dt)
xticklabels(0:6:48)
ylim padded
xlim padded
if z==1
   title('Ambient Air Temp VS Time in Bethlehem PA')
end
if z==2
   title('Ambient Air Temp VS Time in Las Vegas NV')
end
ylabel('Temperature [K]')
xlabel('Time [hours]')

%% Calculation of steady state initial conditions to time step end
%% Input of data Table Values
%Convection
   Vavgg=data(:,4);
   Vavg = interp1(1:EndTime+1,Vavgg,1:1*dt/3600:EndTime+1-1*dt/3600,"linear");
%Sun Rad
   Gss=data(:,6);
   Gs = interp1(1:EndTime+1,Gss,1:1*dt/3600:EndTime+1-1*dt/3600,"linear");
%Sky Rad
   Tdeww=data(:,5);
   Tdew = interp1(1:EndTime+1,Tdeww,1:1*dt/3600:EndTime+1-1*dt/3600,"linear");
%%
t=1;
Tf=(Tinfset(t)+Tset(end,t))/2;
%Interpolation of values
[Pr,v,kf,a]=Interpolator(Tf);

%Conduction
   Rgs=Lgs/Kgs(z); %R" of the ground soil
   Rtot_cond=Rc+Rgs+Rcontact; %R" through all
   qcond=(Tset(end,t)-Tset(1,t))/Rtot_cond;
```

```
%Convection
%Forced
   if Vavg<=5
      h_forced=5.6+4.0*Vavg(t);
   else
      h_forced=7.2*Vavg(t)^0.78;
   end
%Free
   g=9.81;%m/sec
   B=1/Tf;
   Ra_L=g*B*(Tset(end,t)-Tinfset(t))*Length^3/(v*a);
   if Tset(end,t)>Tinfset(t)
      if Ra_L<10^7 && Ra_L>10^4
         Nu_L=0.54*Ra_L^(1/4);
      elseif Ra_L<10^11 && Ra_L>10^7
         Nu_L=0.15*Ra_L^(1/3);
      end
   elseif Tset(end,t)<Tinfset(t)
         Nu_L=0.52*Ra_L^(1/5);
   elseif Tset(end,t)==Tinfset(t)
      Nu_L=0;
   end

   h_free=Nu_L*kf/(Length/4);

   h=(h_forced^4+h_free^4)^(1/4);
   qconv=h*(Tinfset(t)-Tset(end,t));
   Rconv=1/h;
%Radiation
%Sun
   qsun=alpha*Gs(t);
%Sky
   Fcloud=1;%Assumed worst case scenario, no cloud cover
   Epsilon_sky=0.787+(0.764*log(Tdew(t)/273)*Fcloud);
   Tsky=Epsilon_sky^(1/4)*Tinfset(t);
   qsky=sigma*epsilon*(Tset(end,t)^4-Tsky^4);
   Rrad=1/(epsilon*sigma*(Tset(end,t)+Tinfset(t))*(Tset(end,t)^2+Tinfset(t)^2));
%Total
qtot(t)=(-qcond-qsky+qsun-qconv);

for x=(fix(((Lc+Lgs)/NodeStep)):-1:1)%Loop For Depth, x=1 @ Ground Soil lowest depth
   if x==1
      break
   end
```

```
        if x>Lgs/NodeStep
          Tset(x,t)=Tset(x+1,t)-qcond*Rc*(NodeStep)/(Lc);
        end
        if x==Lgs/NodeStep
          Tset(x,t)=Tset(x+1,t)-qcond*(Rcontact);
        end
        if x<Lgs/NodeStep
          Tset(x,t)=Tset(x+1,t)-qcond*Rgs*(NodeStep)/(Lgs-.01);
        end

    end

    %% Calculation of time march
     for t=(2:1:(EndTime)*3600/dt)

Tset(end,t)=Tset(end,t-1)+2*Fo_c*(Tset(end-1,t-1)-Tset(end,t-1))+2*Fo_c*(qtot(t-1))*NodeStep/
Kc;
        Tf=(Tinfset(t)+Tset(end,t))/2;
        [Pr,v,kf,a]=Interpolator(Tf);
          %Conduction
          Rgs=Lgs/Kgs(z); %R" of the ground soil
          Rtot_cond=Rc+Rgs+Rcontact; %R" through all
          qcond(t)=(Tset(end,t)-Tset(1,t))/Rtot_cond;
          %Convection
          %Forced

          if Vavg(t)<=5
            h_forced=5.6+4.0*Vavg(t);
          else
            h_forced=7.2*Vavg(t)^0.78;
          end
          %Free
          g=9.81;%m/sec
          B=1/Tf;
          Ra_L=g*B*(Tset(end,t)-Tinfset(t))*Length^3/(v*a);
          if Tset(end,t)>Tinfset(t)
            if Ra_L<10^7 && Ra_L>10^4
              Nu_L=0.54*Ra_L^(1/4);
            elseif Ra_L<10^11 && Ra_L>10^7
              Nu_L=0.15*Ra_L^(1/3);
            end
          elseif Tset(end,t)<Tinfset(t)
              Nu_L=0.52*Ra_L^(1/5);
          elseif Tset(end,t)==Tinfset(t)
```

```
            Nu_L=0;
        end

        h_free=Nu_L*kf/(Length/4);
        h=abs(kf/(Length/4)*((h_forced*(Length/4/kf))^4+(h_free*(Length/4/kf))^4)^(1/4));
        qconv(t)=h*(Tset(end,t)-Tinfset(t));
        %Radiation
        %Sun
        qsun(t)=alpha*Gs(t);
        %Sky
        Fcloud=1;%Assumed worst case scenario, no cloud cover
        Epsilon_sky=0.787+0.764*log(Tdew(t)/273)*Fcloud;
        Tsky=Epsilon_sky^(1/4)*Tinfset(t);
        qsky(t)=sigma*epsilon*(Tset(end,t)^4-Tsky^4);
        %Total

        qtot(t)=(-qcond(t)-qsky(t)+qsun(t)-qconv(t));

    for x=(fix(((Lc+Lgs)/NodeStep)):-1:1)%Loop For Depth, x=1 @ Ground Soil lowest depth
        if x==1
            break
        end

        if x>Lgs/NodeStep %Interior COncrete Nodes
            Tset(x,t)=Fo_c*(Tset(x+1,t-1)+Tset(x-1,t-1))+(1-2*Fo_c)*Tset(x,t-1);
        end
        if x==fix((Lc+Lgs)/NodeStep)-Lc/NodeStep
            Tset(x,t)=Fo_c*Tset(x+1,t-1)+Fo_gs(z)*Tset(x-1,t-1)+(1-Fo_c-Fo_gs(z))*Tset(x,t-1);
        end
        if x<Lgs/NodeStep%Interior GS Nodes
            Tset(x,t)=Fo_gs(z)*(Tset(x+1,t-1)+Tset(x-1,t-1))+(1-2*Fo_gs(z))*Tset(x,t-1);
        end

    end
  end
%% Graphing of time march data
figure(z+2)
tiledlayout(1,3);
nexttile
plot(Tset(:,1),depth);
floor=refline(0,-114);
floor.Color="b";
floor.LineStyle=":";
floor=refline(0,0);
```

```
floor.Color="r";
floor.LineStyle=":";
title('Midnight day 1 (0 hrs)')
xlabel('Temperature [K]')
ylabel('Depth [cm]')
ylim padded
xlim padded

nexttile
plot(Tset(:,24*3600/dt),depth);
floor=refline(0,-114);
floor.Color="b";
floor.LineStyle=":";
floor=refline(0,0);
floor.Color="r";
floor.LineStyle=":";
title('Midnight day 2 (24 hrs)')
xlabel('Temperature [K]')
ylabel('Depth [cm]')
ylim padded
xlim padded
nexttile
plot(Tset(:,36*3600/dt),depth);
floor=refline(0,-114);
floor.Color="b";
floor.LineStyle=":";
floor=refline(0,0);
floor.Color="r";
floor.LineStyle=":";
title('Noon day 2 (36 hrs)')
xlabel('Temperature [K]')
ylabel('Depth [cm]')
ylim padded
xlim padded
sgtitle('Temperature vs Depth in '+location(z));
figure(z+4)
plott=1:1:EndTime*3600/dt;
plot(plott,Tset(end,:));
floor=refline(0,TsMAX+273);
floor.Color="r";
floor.LineStyle=":";
axis([1  2400 0 inf])
xticks(0:6*3600/dt:EndTime*3600/dt)
xticklabels(0:6:48)
```

```
  xtickangle(360)
  title('Sidewalk Surface Temperature in '+location(z))
  xlabel('Time [Hours]')
  ylabel('Temperature [K]')
  legend('T(t)', 'Unsafe Temperature Above This Line');
  ylim padded
  xlim padded
end
%%
%Temp Distribution for all t visualizer
% for i=(1:1*3600/dt:EndTime*3600/dt-1)
%     hold on
%     figure(10)
%     plot(Tset(:,i),depth);
%     hold off
% end
% floor=refline(0,-114);
% floor.Color="b";
% floor.LineStyle=":";
% floor=refline(0,0);
% floor.Color="r";
% floor.LineStyle=":";
% title('Temperature VS Depth for all t[hrs] in '+location(1))
% xlabel('Temperature [K]')
% ylabel('Depth [cm]')
% ylim padded
```