Mathematical Modeling of Road to Plastron Heat Transfer and its Effect on Internal Temperatures of *Malaclemys terrapin terrapin*

Abstract

Malaclemys terrapin is a vital organism to the Barnegat Bay Ecosystem as a keystone species in the food chain and an indicator of environmental issues. They populate marshes and, during their nesting season of June-August, the females of the species come on land and cross roads to find suitable (sandy) sediments in which to lay their eggs. Road temperatures during this time period can get as high as 70+°C and previous studies have documented deformities in the eggs of some turtle species when incubation temperatures exceeded 35°C. This study was conducted to test the hypothesis that terrapin eggs can be affected by high road temperatures while the mother crosses asphalt roads using mathematical modeling to determine if her internal temperatures can reach harmful levels. Theoretical data was gathered using a conduction model and experimental data was gathered measuring the inside of empty terrapin shells on a hot plate. The theoretical and experimental data were compared and the model was shown to be accurate for the medium shell used. In order to properly analyze a terrapin walking across the road however, a more advanced model was created after finding an approximation for radiation heat transfer and applying the model to the walking pattern of a terrapin. The results suggest that internal temperatures of road-crossing terrapins can reach harmful levels with the 45°C road surface model reaching 35°C internal temperature in 110 seconds and the 70°C road surface model reaching 35°C in only 35 seconds.

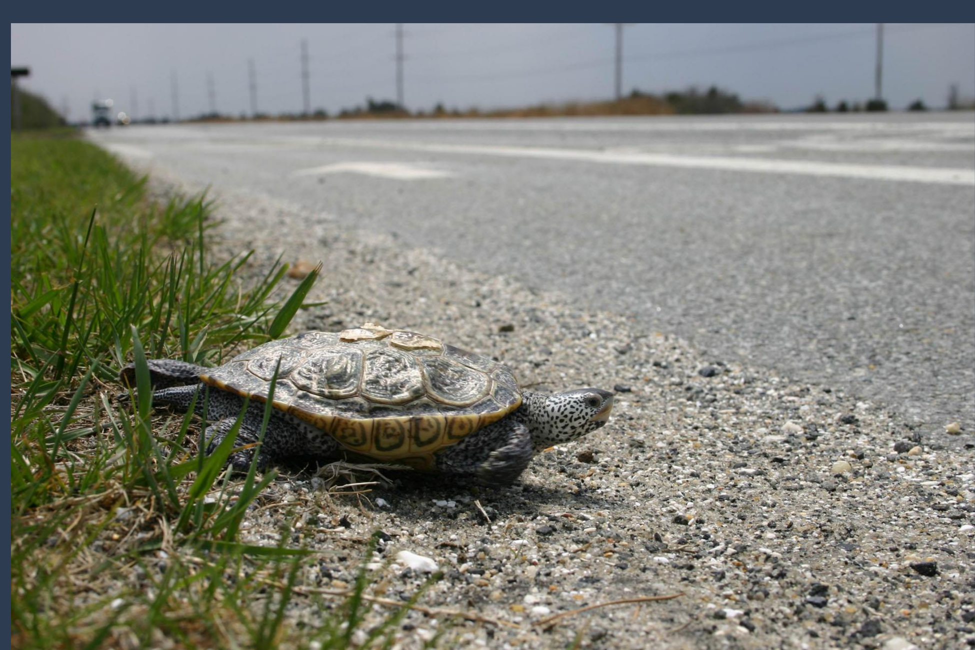

Figure 1: A female *Malaclemys terrapin terrapin* starting to cross a road. Photo from DE Center for the Inland Bays, 2017.

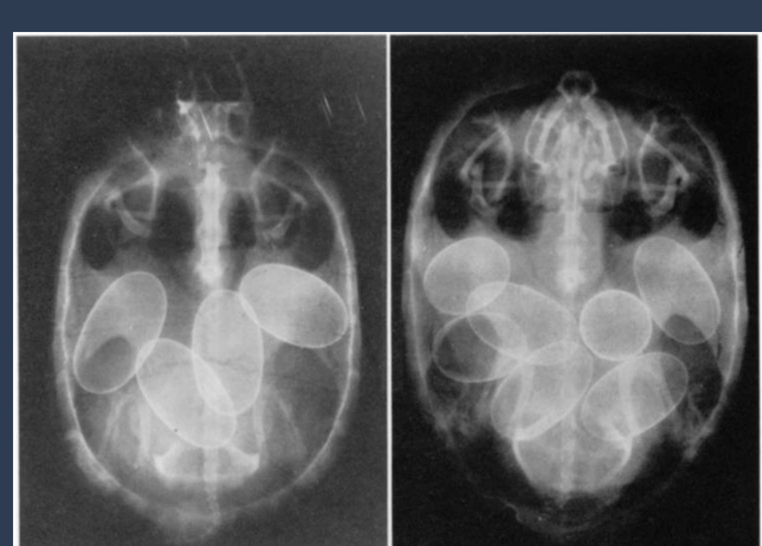

Figure 2: X-Ray of two female *Sternotherus odoratus*, showing the eggs stored towards the back of the mother (Gibbons & Greene 1979).

Introduction

Malaclemys terrapin, or the diamondback terrapin, is a vital species of marsh ecosystems, being a keystone species and an indicator of a variety of environmental issues (Basile et al. 2011). They live in estuarine systems all along the East coast from about Cape Cod, Massachusetts to Corpus Christi, Texas, including around the Florida Keys. The numbers of *M. terrapin terrapin* have been declining for several years in New Jersey among other areas due to anthropogenic factors and has dipped so low that in 2016, a status review recommended the species for Special Concern conservation status (Wurst 2016). Therefore, it is essential to fully understand the impacts that human development can have on *M. terrapin terrapin* so that steps may be taken to shield the species from further decline.

During nesting season, *M. terrapin terrapin* adult females must cross roads in order to find suitable nesting sites (Figure 1). They prefer nesting in sandy soils, which are not found in the marsh but are found across roads in developed areas, such as yards. These road crossings happen during the late summer, during which road temperatures can reach extremely high temperatures. A study from Florida, a state within the range of *M. terrapin*, measured temperatures above 60°C for asphalt (Breithaupt 2010). Previous experimentation with *Lepidochelys olivacea* (olive ridley sea turtle) has shown that turtle embryos can experience birth complications or even die after experiencing incubation temperatures higher than 35.0°C (Valverde et al. 2010). A concern lies in the plastron, or bottom portion of the shell, sitting atop the hot road for too long and heating up the area where fertile eggs lie in a female terrapin (Figure 2). However, there are no previous studies relating to internal temperatures of terrapins during road crossings. This study aims to investigate whether the internal temperatures of the terrapins can reach 35.0°C or higher temperature and potentially cause significant damage to the *M. terrapin terrapin* embryo during road crossings in nesting season. This study will use mathematical and computational methods to ensure maximum accuracy and compare theoretical results to experimental results to determine if the model is accurate.

Objective

Use mathematical and computational methods to model the results of a terrapin crossing a road.

Methodology

Experimental Data Collection

- Road temperature (°C) collected at various times at 195 Cedar Bridge Road in Manahawkin, NJ on July 24, 2019 through July 27, 2019.
  - Air temperature, ground temperature, 2.5 cm, 5.0 cm, 7.5 cm, 10.0 cm temperatures
  - Also sourced from studies in other *M. terrapin* native states
- Testing done using a hot plate with two empty terrapin shells (small and medium) (**Figure 3, Figure 6**)
  - 45°C and 75°C tested with each shell to represent the range of road temps in the range of *M. terrapin*
  - Small shell to represent male and medium to represent female
  - Temperature found using digital temperature sensor and recorded at 5-second intervals for about 500 seconds
  - Data entered into Excel and matplotlib, numpy, and seaborn were used to graph the data and create a second-degree best fit polynomial for the data

Model Creation

- Conduction Simulation
  - Equation found for conduction across a parallel-plate system (Gates 2003):

$$q = kAt\frac{T_1 - T_2}{d}$$

  - Entered into Python program that ran the equation recursively for a specified amount of time
  - Result graphed against experimental data for each shell and temperature, percent error calculated for each
  - Determined that the equation was a good approximation for conduction through a terrapin shell
- Radiation Implementation
  - Placed terrapin shell atop two crucibles and took internal temperature in the same manner as conduction. Also found air temperature below terrapin shell (**Figure 4**)
  - Compared experimental internal temperature data of that trial with theoretical data using the conduction equation with air temperature below plastron
  - Determined that using conduction with air temperature is a valid approximation for radiation
  - Analyzed air temperature as compared to asphalt temperature from summer measurements and determined that the temperature at 5 cm can be approximated by taking the ground temperature and adding 8.63°C
  - Created a variable that switches between the radiation method and the conduction method depending on the pattern input and created pattern after analyzing a captive terrapin walking (**Figure 5**)
- Final visualization
  - Added methods to a Plastron class that would update the numbers and output different graphs including a lineplot and a heatmap

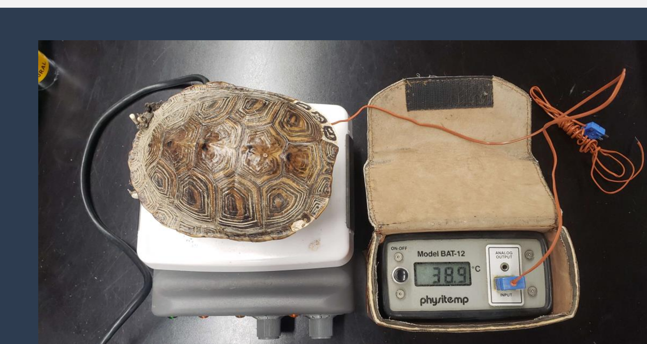

Figure 3: The setup for the conduction tests, with the medium-sized shell atop the hot plate and the thermocouple reader inside the shell.

Figure 4: The setup for the radiation tests, with the medium-sized shell suspended on two non-conductive crucibles approximately 5.0 cm in the air.

Figure 5: A *Malaclemys terrapin terrapin* walking. In the first image, the terrapin is sitting still as they often do on roads. The second image depicts the terrapin dragging his plastron on the table as he walks, showing that the back of the plastron is always affected by radiation.

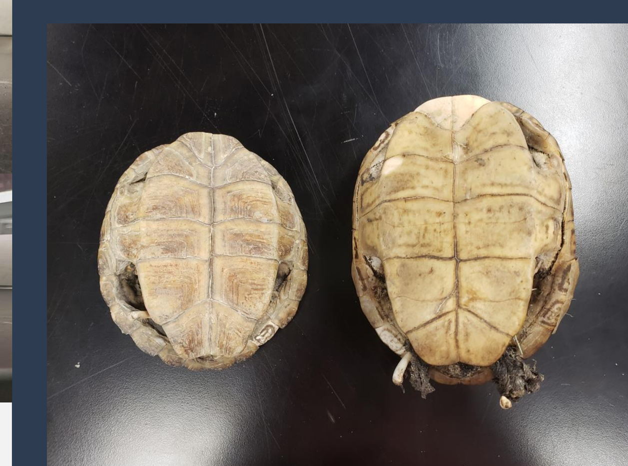

Figure 6: Size comparison between the small and medium-sized shells.

Results

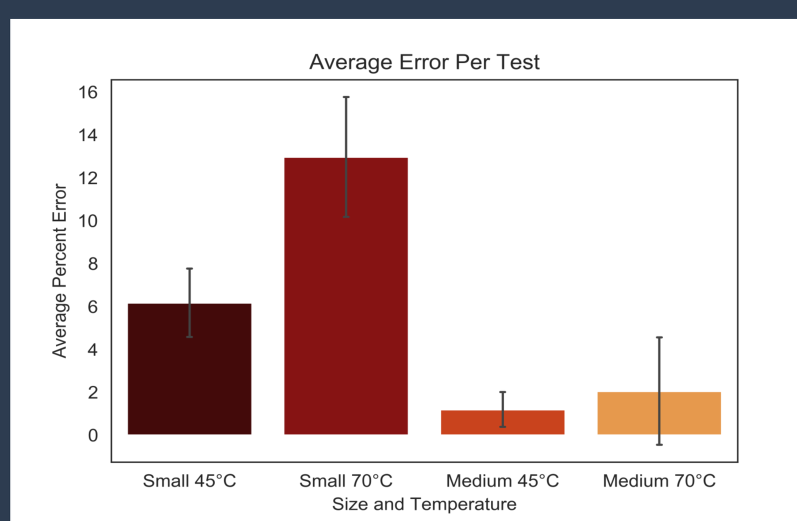

Figure 7: Average percent error for each second across each test (n=2131). Error bars were created using standard deviation. An ANOVA was used to compare the accuracy of the small and medium tests for each temperature and both returned a P-value less than 0.0001, indicating that the medium model is more accurate than the small model.

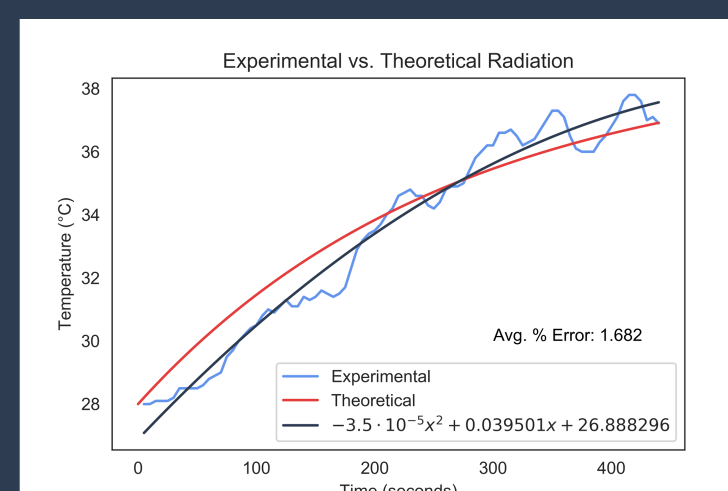

Figure 10: Temperature curve for the radiation trial. Experimental data was gathered by placing the shell atop crucibles and theoretical data was calculated using the conduction equation but with the air temperature below the plastron as hot plate temperature (39◦C). According to the low error, this method using conduction with air temperature to approximate radiation is accurate.

Table 1: Temperature (°C) data was gathered on asphalt at various times throughout the day from July 24, 2019 to July 27, 2019 in Manahawkin, NJ (n=10)

Date	Time	Air Temp	Ground	2.5 cm	5 cm	7.5 cm	10 cm
24-Jul	18:30	29.4	41.4	32.8	32.0	30.9	30.4
26-Jul	10:00	27.7	41.3	35.9	35.4	33.6	33.4
26-Jul	11:00	29.5	44.4	35.5	34.9	34.2	34.0
26-Jul	12:00	30.4	47.3	35.3	34.8	33.4	31.8
26-Jul	13:00	31.1	45.8	35.6	34.6	34.0	33.7
26-Jul	14:00	31.4	44.1	34.2	33.8	32.2	32.0
26-Jul	15:00	29.7	44.5	33.8	33.4	32.0	31.4
27-Jul	10:00	27.3	39.8	33.6	33.2	32.5	32.2
27-Jul	11:00	28.0	36.4	31.5	31.3	30.6	29.8
27-Jul	12:00	28.7	43.7	33.4	33.2	31.8	31.4

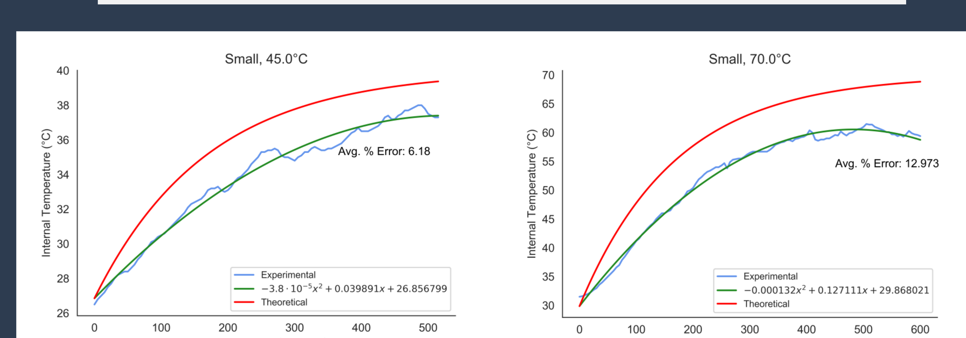

Figure 8: The temperature (°C) curves for the small shell with a hot plate temperature of 45.0°C and 70.0°C, respectively, with experimental data gathered at 5-second over about 500 seconds (n=100). The average percent errors were 6.180% and 12.973%, indicating that the model was not entirely accurate.

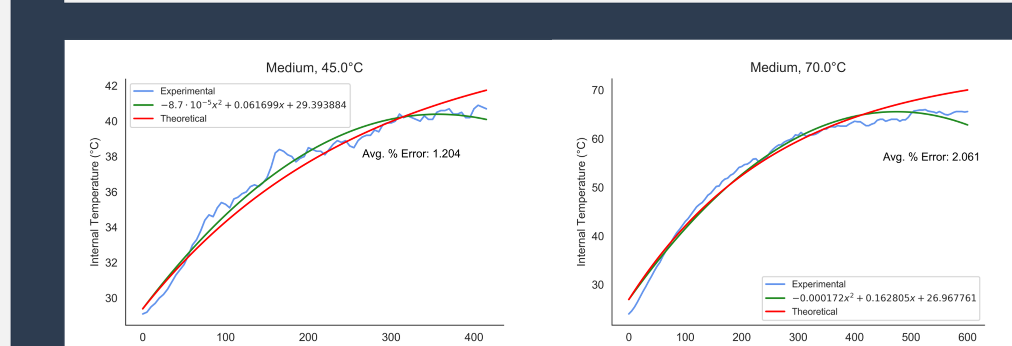

Figure 9: The temperature (°C) curves for the medium shell with a hot plate temperature of 45.0°C and 70.0°C, respectively, with experimental data gathered at 5-second over about 500 seconds (n=100). The average percent errors were 1.204% and 2.061%, indicating that the model fit the experimental data accurately.

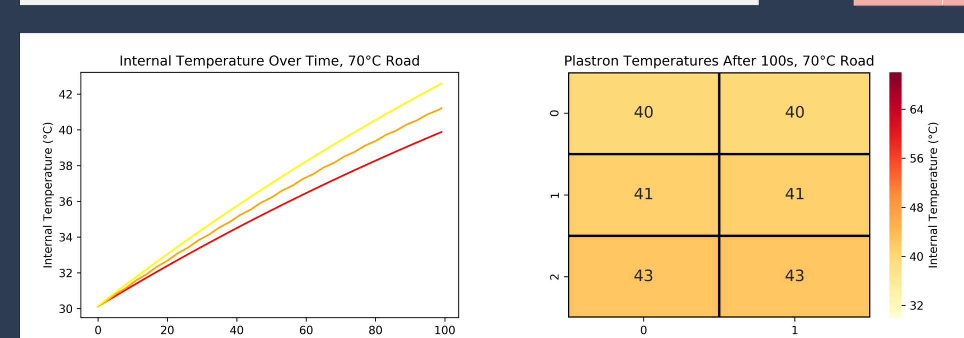

Figure 11: Representation of a terrapin's temperature after 100 seconds on a 70°C road over time and by section of the plastron. The top of the heatmap (front) is at the lowest temperature because the temperature is calculated using exclusively radiation whereas the middle section used conduction for half of the iterations and the back section used conduction the entire way.

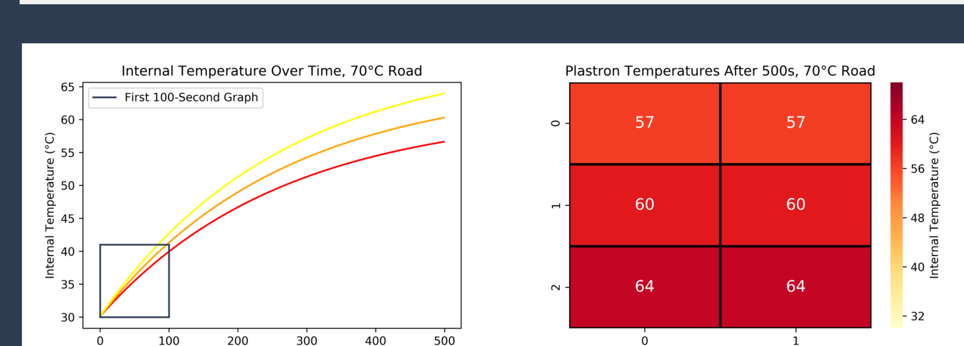

Figure 12: Representation of a terrapin's temperature after 500 seconds of heating on a 70°C road. The previous 100-second lineplot is shown within the box on this lineplot. As the model progresses, it adds to the lineplot and generates a new heatmap each second. This can be combined into an animation as well.

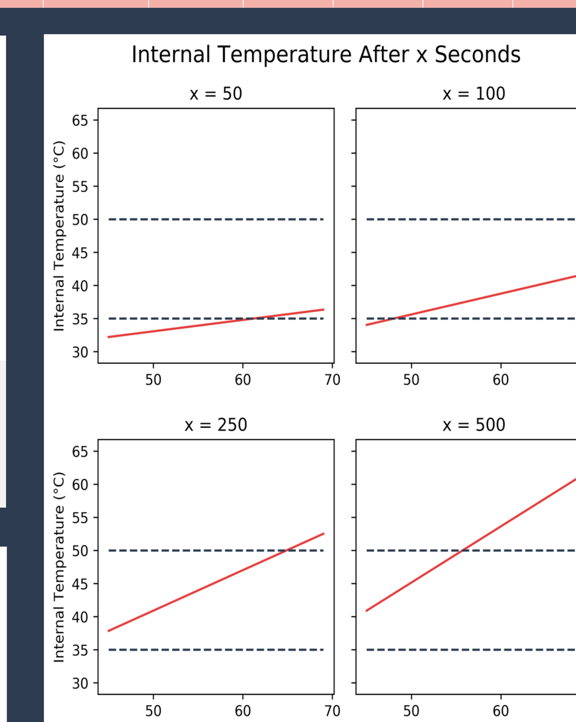

Figure 13: Subplots showing the modeled internal temperature after x seconds by road temperature along with 35°C and 50°C internal temperature markings. For example, a female turtle can stay on a road remain under 35°C as long as the road temperature is less than 60°C for 50 seconds or less than 47°C for 100 seconds.

Discussion

The results of the initial conduction trials in **Figures 7** using small and medium shells showed that the model was only accurate for the medium shell. This was likely because the smaller shell used for this study had an excess of organic matter and peeling scutes (plates of keratin) on the inside that impacted the thermocouple's ability to measure the temperature on the top of the plastron. It also obscured the shell's contact with the heat plate, causing it to be raised slightly above the plate and thus causing the measured temperature to change slower than the model predicted. Because of this, only the medium shell was used for the rest of the study.

Since the model constructed using the conduction equation with this air temperature was shown to be accurate as shown in (**Figure 10**), it verified this method of calculating radiative heat transfer and therefore could be added to a combined model.

The final model taking into consideration both methods of heat transfer (conduction and radiation) for different sections of the plastron based on the walking pattern is represented visually in **Figures 11, 12, and 13**. Comparing the 100-second graphs to the 500-second graphs, it can be seen that the temperatures of the three vertical plastron sections diverge because the small differences due to part of the plastron being above the asphalt at some points accumulate. It is because of this that the average of the middle and back sections was used for calculations relevant to temperature below the eggs in **Figure 13**.

The subplots of **Figure 13** show that if a turtle were to walk along a hot surface for 50 seconds, she would experience harmful temperatures for her eggs if the road was hotter than around 60.0°C. If she was to sit on a surface for 100 seconds, which is not an uncommon occurrence given their tendency to retreat into their shell upon the passing of a car and the high levels of activity on many roads within their range, any road temperature above about 50°C would cause harm. The 250- and 500-second models are less likely occurrences, but can still happen on a long stretch of asphalt or an area with a large amount of development.

Conclusion

In conclusion, the final model is accurate for both conduction and radiation modeling based on comparisons between theoretical and experimental data and can be used to generate a variety of visualizations including an animation with a heatmap and a lineplot and a prediction of how long a turtle can stay on a road based on the temperature of the road and any threshold. The results show that terrapin internal temperatures can easily reach harmful levels for egg incubation. In the future, the model can be tested using different size shells to make it more applicable. This project could also be expanded by taking a more in-depth look at terrapin development and how exactly these temperatures can harm baby terrapins.

Figure 14: Baby terrapins already have an extremely low survival rate to adulthood, so research such as this into the reasons they may have unsuccessful childhoods is important to understand how to increase their survival rate.

Acknowledgements

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