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Field Procedure for Estimating the Measurement Area of Non-Contact Temperature Sensors

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Abstract

Transportation departments across the United States have installed sensors mounted on towers by the roadside to measure road surface temperatures. Since no guidelines exist for verifying the accuracy of such measurements, agencies are forced to accept claims made by vendors. To correct this situation, the Idaho Transportation Department (ITD) contracted with Boise State University (BSU) to test the accuracy of the non-contact, infrared temperature sensors installed throughout Idaho. Before collecting independent temperature data, BSU devised an easy-to-use procedure for determining the effective area viewed by the infrared sensors. According to ITD, the vendor claimed that at a distance of 10 m between the sensor and the road surface, the diameter of the effective area viewed by the sensor would be 80 cm. BSU's field experiment revealed that the sensor's viewing area was much larger than that claimed by the vendor. The discrepancy suggests that other claims made by the vendor regarding the accuracy and precision of their measurements cannot be relied upon and transportation departments will need to conduct independent tests to verify such claims.

Introduction

Background

Many state departments of transportation have installed non-contact temperature sensors as a part of their Road Weather Information Systems (RWIS). Many of these sensors are based on infrared technology and measure roadway temperatures by processing infrared signals emitted by the road surface. Vendor documents describe the accuracy and precision of these sensors, but there are no independent guidelines available to transportation departments to verify the claims made by vendors. Consequently, the Idaho Transportation Department (ITD) contracted with Boise State University (BSU) to verify the accuracy of the temperature sensors installed at RWIS stations in the state. A literature search revealed that there is very little documentation on field testing of non-contact pavement temperature sensors.

A National Cooperative Highway Research Program (NCHRP) report on test methods for evaluating field performance of RWIS sensors has a section on field testing procedures for pavement sensors. Five different field tests are listed for the "complete" testing of sensors for varying conditions, but the tests all pertain to sensors that are installed in the pavement, as opposed to those mounted on poles away from the carriage way [1]. Similarly, Rajabipour et al. [2] used a temperature sensor along with three electrical sensors to develop a material sensing and health monitoring system for concrete materials; the temperature sensor was embedded in the concrete. Other examples of sensors embedded in the pavement for measuring pavement temperatures or detecting ice formation on the road surface include Troiano et al. [3] and Sherif and Hassan [4].

The Battelle [5] corporation has evaluated ITD's RWIS, but their work was related to the integration of RWIS data with non-transportation weather data. The integration project was intended to solve various problems faced by ITD, but did not address potential inaccuracies in the data collected by the RWIS sensors.

Bogren et al. [6] quantified the effect of shading on pavement surface temperatures and present a formula to calculate the difference in pavement surface temperatures between areas exposed to and shaded from the sun as a function of solar elevation. They present the following formula to calculate the road surface temperature difference (RST_{diff}) as a function of solar elevation, β:

$$RST_{diff} = -2.7 + 0.46 \cdot \beta \quad in\ °C$$

This formula was used to compute the difference in temperatures due to shading at the Horseshoe Bend Hill RWIS site on State Highway 55 in Idaho. The solar elevation at this location (43° 54' 53" N – 116° 11' 52" W) on May 20, 2010, at 10:30am, was 43.81°. With β equal to 43.81, RST_{diff} was calculated to be 17.45° C. Based on this information, the authors of this study ensured that there was no shading of the pavement during data collection.

Bättig [7], in an article presented at the combined Fourth National Conference on Surface Transportation Weather and the Seventh International Symposium on Snow Removal and Ice Control Technology in June, 2008, reported on an expert system for winter maintenance that forecasts the road conditions for the next 24 hours. Temperatures used in Bättig's study were measured at a depth of 0.7 m under the road surface.

Need for Study

Since the literature does not describe how non-contact pavement temperature sensors can be tested, a new procedure had to be defined. But before collecting temperature data using alternative devices, the extent of the area viewed by the infrared sensor had to be determined. Literature describing such a procedure was also found to be lacking. For example, Jonsson and Riehm [8] reported results from their temperature measurement tests at an RWIS site in Sweden. They used temperature probes installed at depths of 2 mm and 0.3 mm as well as an IR camera and an IR thermometer mounted on a mast at different heights on the roadside. The diameter of the measurement spot side of the IR thermometer was given without any explanation. In contrast to the work presented by Jonsson and Riehm [8], this paper describes how the measurement area of remote, infrared temperature sensors can be estimated.

Infrared Signal Processing

An infrared sensor receives signals from a large area of the pavement around the point where the line of sight of the sensor lens hits the ground. Signals received from areas away from this center point will have a decreasing effect on the calculated value of the temperature. It was postulated that an area can be defined such that measurements from locations outside the area will have a minimal effect on the average temperature calculated from a particular set of measurements. Determination of the extent of such an area is useful to agencies that wish to verify the accuracy of their RWIS sensors: Any desired temperature measurement using an alternative device can be limited to this area. This note describes a process that transportation departments can use to rapidly determine the measurement footprint of infrared temperature sensors. The procedure involves estimation of the full width at half maximum of the Gaussian response function of the sensor.

Full Width at Half Maximum (FWHM)

It was assumed that an infrared sensor makes use of a Gaussian spatial response function in order to estimate the temperature of the measured area. Sensors that depend on infrared radiation, process signals received from an area defined by the full-width-at-half-maximum (FWHM) of a Gaussian function to estimate the average response. In signal processing, FWHM is defined as the frequency range where the power is half the maximum. For example, Keranen et al. [9] report that the field of view (FOV) of the sensor they used in their study was approximately 10° based on the FWHM of the sensor. The FWHM varies with distance from the sensor lens, as depicted in Figure 1.

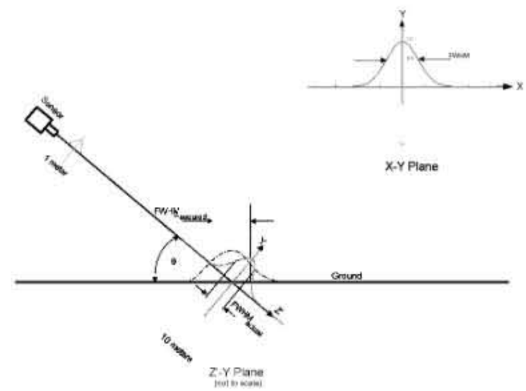

Figure 1. Measured Versus Actual FWHM

This function is symmetric with respect to the x and y axes and grows with the distance from the sensor as measured along the third axis, Z. The symmetry of the function results in $\sigma = \sigma_x = \sigma_y$. The standard deviation, σ, is dependent on z, the distance from the sensor. That is, $\sigma = \sigma(z)$.

Because the sensor is mounted on a pole on the side of road, the road surface is not perpendicular to its line of sight. Figure 1 shows the projection of the response function on the ground. The projection creates a situation where $\sigma_x \neq \sigma_y$; the projection of the Gaussian response function on the floor is elliptical. To measure the FWHM along the ground, a geometric correction must be applied. The correction depends on the angle between the camera's Z axis and the ground, according to the geometry shown in Figure 1.

Modeling Procedure

The response of the sensor was measured by sliding an object along the ground into the view of the sensor, as shown in Figure 2. The object shown in the figure is a polystyrene foam board but, in general, could be substituted by a variety of other materials. What is essential is the use of an object that will provide a thermal contrast between the road pavement and the surface of the object. Initially the sensor "sees" just the ground at ambient temperature. As the board is translated into view of the sensor, it measures the temperature of the combined view, the ambient ground temperature and the temperature of the board, which can be quite different in temperature. When the board is fully translated into the view of the sensor, the sensor will only detect the board at its temperature, T_{Board}.

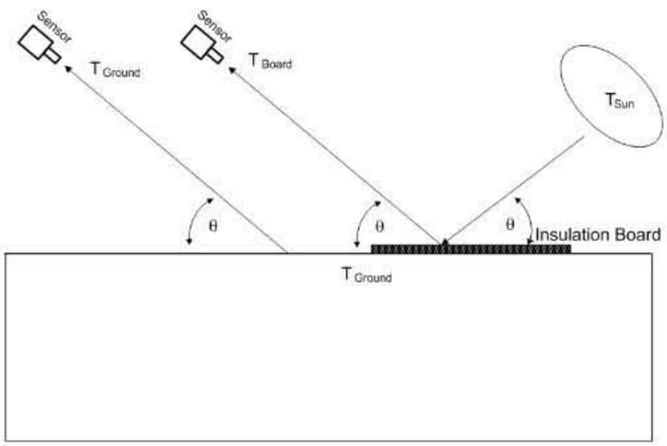

Figure 2. Temperature of the Board versus Temperature of the Ground

A key point is that the emissivity and reflectivity of the ground (asphalt pavement) and the sliding object (insulation board) will be different and as such, the temperatures of the two surfaces will be different. For example, the ground temperature, T_{Ground}, could be 10° C and T_{Board} could be 20° C. The emissivity of the asphalt road surface can be between 0.8 and 0.99 [8] and reflectivity around 0.08 [10]. The insulation board also has high emissivity and low reflectivity, but its values will be different from that of the road surface; hence, a thermal contrast between the two surfaces will be created. Additionally, the board with its top surface painted black will absorb more sunlight and will be at a higher temperature than the pavement surface. Further, as noted by Kranen et al. [9], the traditional optomechanical design of IR temperature measuring systems is optimized for situations in which the device is thermally stable and the measured targets are significantly warmer than the device. These conditions were ensured during the lab and field tests reported in this paper. Figure 3 depicts the field setup using a plywood sheet, one side of which was painted black. Plywood was later replaced by a 2.54 cm thick polystyrene foam board for the field test reported in this note.

Figure 4 depicts how the sensor measures different temperatures for the two surface types that appear in its field of view as the board is slid forward. Let *T2(z,x)* be the temperature of the surface of the insulation board and *T1(z,x)* be the temperature of the road surface.

Figure 3. Insulation Board for Temperature Measurement in the Field

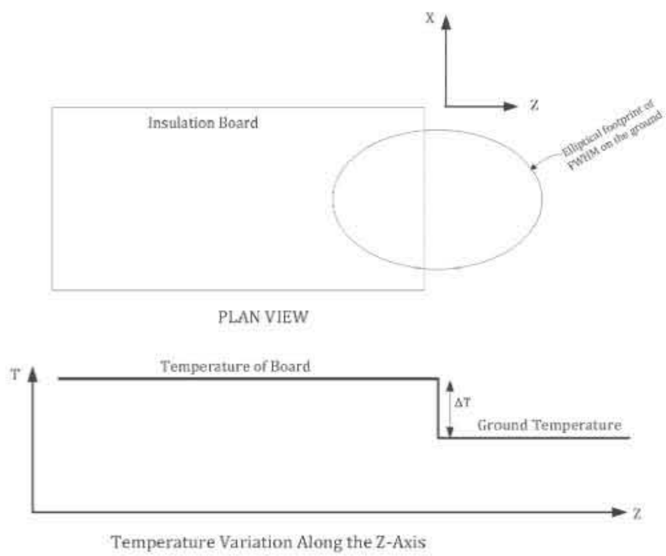

Figure 4. Sliding the Board into the Sensor's Field of View

The temperature, when the forward edge of the board is at location *z*, *T(z)*, is given by Equation (1). This location was measured with reference to a point in the ground immediately below the sensor. The temperature at each point *T(z,x)* was multiplied by a Gaussian weighting function to calculate *T*.

$$T(z) = \int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty} T(\alpha,\beta)\cdot e^{-\left(\frac{\alpha^2}{2\sigma_\alpha^2}+\frac{\beta^2}{2\sigma_\beta^2}\right)} d\alpha d\beta = \int_{-\infty}^{z}\int_{-\infty}^{+\infty} T2(\alpha,\beta)\cdot e^{-\left(\frac{\alpha^2}{2\sigma_\alpha^2}+\frac{\beta^2}{2\sigma_\beta^2}\right)} d\alpha d\beta$$
$$+\int_{z}^{+\infty}\int_{-\infty}^{+\infty} T1(\alpha,\beta)\cdot e^{-\left(\frac{\alpha^2}{2\sigma_\alpha^2}+\frac{\beta^2}{2\sigma_\beta^2}\right)} d\alpha d\beta \qquad (1)$$

To simplify the model, it was assumed that $T2(\alpha,\beta)$ was constant on the top of the board and $T1(\alpha,\beta)$ was also constant on the road. Since the goal was to compute the difference in temperatures between the two surfaces, ΔT, it was further assumed that $T1(\alpha,\beta) = 0$. With these assumptions, Equation (2) was obtained to measure the difference in temperature.

$$\Delta T(z) = \int_{-\infty}^{z}\int_{-\infty}^{+\infty} Ae^{-\left(\frac{\alpha^2}{2\sigma_\alpha^2}+\frac{\beta^2}{2\sigma_\beta^2}\right)} d\alpha d\beta = A\int_{-\infty}^{+\infty} e^{-\frac{\beta^2}{2\sigma_\beta^2}} d\beta \int_{-\infty}^{z} e^{-\frac{\alpha^2}{2\sigma_\alpha^2}} d\alpha$$
$$= B\int_{-\infty}^{z} e^{-\frac{\alpha^2}{2\sigma_\alpha^2}} d\alpha = \frac{\sqrt{\pi}}{2} B\cdot erf\left(\frac{z}{\sqrt{2}\sigma_x}\right) = K\cdot erf\left(\frac{z}{z_0}\right) \quad (2)$$

where,

DT is the difference in temperature between the two surfaces,

$$K = \frac{\sqrt{\pi}}{2}B$$

and A and B are constants.

$$z_0 = \sqrt{2}\sigma_z$$

The variable z_0 can be used to estimate the FWHM of the Gaussian function used by the sensor, but this FWHM will be with respect to the ground. Since this was what was actually measured in this experiment, it is denoted as $FWHM_{measured}$. The FWHM actually used by the sensor was along the longitudinal axis of the sensor, and is denoted by $FWHM_{actual}$. The measured FWHM value needed to be corrected to get the value corresponding to the longitudinal axis of the sensor lens. Equations used to compute these quantities are shown in Equation (3).

$$FWHM_{measured} = 2\times\sqrt{2\times\ln(2)}\sigma_z = 2.35\sigma_z = 2.35\frac{z_0}{\sqrt{2}}$$
$$FWHM_{actual} = \sin\theta\cdot FWHM_{measured} \quad (3)$$

where,

q is the angle between the line-of-sight of the lens and the ground.

In the above formulation, the constant temperature on the insulation board is denoted by A, and the temperature on the ground is also constant. The change in temperatures computed by Equation (2) is relative to the temperature on the ground. The goal of the modeling effort was to estimate z_o from Equation (2). But Equation (2) had to be modified before it could be fitted to the temperature data collected by sliding the board into the field of view.

The plot of the temperature data was expected to start from a low point corresponding to the bottom left leg of the Gaussian curve and increase to a maximum point corresponding to the top of the Gaussian curve. Midway between these low and high points, an inflection point was expected in the temperature plot. Equation (2) was modified to measure the temperature at fixed distances away from this midpoint. The modified formula is Equation (4). In the modified equation, the variable z is the distance between the subject location and the location of the mid-temperature value. Furthermore, since the actual location of the center point viewed by the sensor may be different from the one marked in the field, an offset correction needed to be introduced in the formulation. Equation (4) incorporates all of these changes.

$$T(z) = K\cdot erf\left(\frac{abs(z-offset)}{z_0}\right) + T_{midpt.} \quad (4)$$

There are four parameters in Equation (4): K, z_0, $offset$, and T_{midpt}. A least squares fitting of Equation (4) was performed in order to fit a Gaussian response model to the observed temperature data that were collected using a sensor in a lab and on the outside pavement. The square root of the sum of squared deviations between the estimated and observed values was minimized using the EXCEL Solver function. Values of the four unknown parameters were varied when computing the minimum.

Data Collection in a Lab

Before going out to the field, the suggested procedure was tested inside a lab in the Micron Engineering Center building at BSU. The distance between the sensor and the object was kept at 1 m. The sensor was set up on a table such that the z-axis was orthogonal to a room wall. A thin aluminum sheet was leaned against the wall. For purposes of this lab experiment, this sheet was considered to be the ground. A Masonite board was then slid over the aluminum sheet in 15 cm increments from right to left. A heater was also placed behind the aluminum sheet to create a temperature differential between the aluminum sheet and the Masonite board. The experimental setup is depicted in Figure 5.

Results from the Lab Experiment

Since there was no inclination between the sensor's z axis and the "ground", no correction for the angle of inclination was needed when using Equation (3) to calculate FWHM. That is, $FWHM_{ground} = FWHM_{longitudinal}$, in this case. The fitting of Equation (4) to the data collected in the lab is depicted in Figure 6. The optimized values of parameters, K, z_0, *offset*, and T_{midpt} were 12, 6.1, 3.3, and 36, respectively. The value of z_0 yielded 10.1 cm as the FWHM. The vendor-suggested value at a distance of 1 m between the sensor and the ground is 8 cm. The model estimated value of 10.1 cm was close to the suggested value.

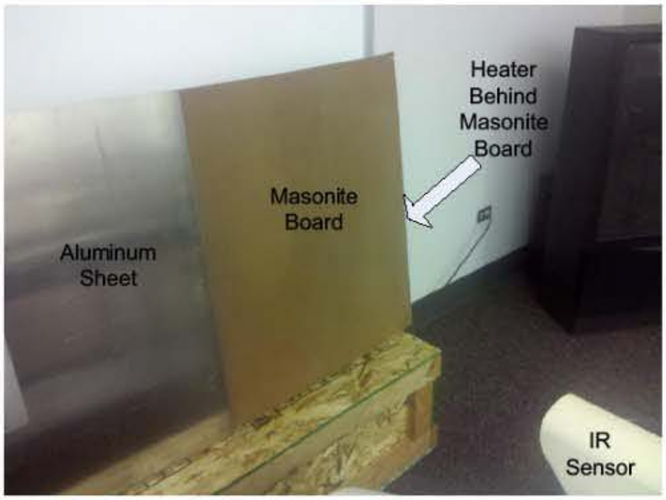

Figure 5. Laboratory Experimental Setup

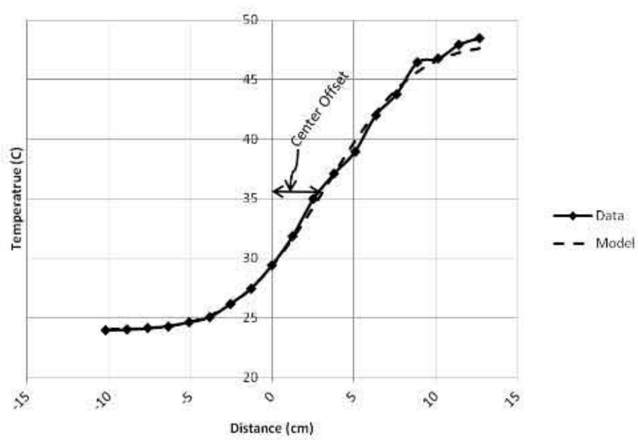

Figure 6. Modeling of the Lab Data

The "Center Offset" in Figure 6 is a measure of the inaccuracy in locating the center point of the field of view of the infrared sensor using the laser pointing device. As the figure shows, T_{midpt} was not observed at a distance of 0 cm but rather at an offset of 3.3 cm to the right of the presumed center point. The center offset is a measure of the error in using the laser pointing device to find the center point of the field of view; it does not, however, affect the estimation of the FWHM.

Data Collection in the Field

The observed data for the modeling exercise was obtained from the experiment performed on April 1, 2011. During the experiment, the center point of the area viewed by the sensor was located first. A laser pointing device mounted on the sensor lens was used to locate the center point. The insulation board was approximately 122 cm wide, 244 cm long, and 2.5 cm thick. One side of the board was painted black and the experiment was conducted on a clear, sunny day to ensure no confounding effects due to cloud cover. First, a straight line was drawn by joining the center point with another point directly below the sensor. This line was extended beyond the center point and marked at 30.5 cm intervals between -183 cm and +183 cm relative to the center point. The top edge of the board was then placed at the -183 cm mark, and temperature measured by the sensor was recorded. The procedure was repeated by moving the top edge of the board to other marks until the +183 cm mark on the line. The temperature data were then plotted and a model fitted. The results are shown in Figure 7.

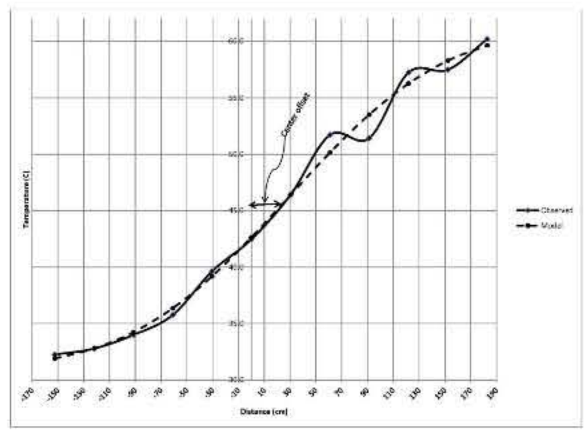

Figure 7. Modeling of the Field Data

Field Data Results

The figure only shows the data between -152 cm and -183 cm since the lowest and highest temperatures were recorded at these points. It can be seen from Figure 7 that the observed data in the lower half of the curve exhibit the expected trend and fit the model well. Data on the upper half are not as well behaved as in the lower half. The center offset of 28.5 cm indicates that the actual center point of the field of view was 28.5 cm away from the sensor relative to the presumed center point of the sensor's field of view, as estimated by the laser pointing device.

The values for K, z_0, *offset*, and T_{midpt} that resulted in the best fit were 27.3, 136.5, 28.5, and 46.1, respectively. This value of z_0 gives 226.8 cm as the FWHM on the ground. With 35.51° as the angle q in this experiment, the resulting $FWHM_{transverse}$ was 131.7 cm. The distance between the ground and the sensor was 7.22 m. According to the vendor's rule of a diameter of 80 cm at a distance of 10 m, the expected measurement area diameter should have been close to 58 cm. The model estimated value is, thus, more than double the suggested value.

Conclusions and Recommendations

Currently, state transportation departments have no guidelines to verify the accuracy of infrared temperature measuring devices that are part of road weather information systems (RWIS) installed in many states in the U.S. If a transportation department wants to use an alternative device to record temperatures, it will be difficult to make such measurements such that the two sets of measurements are comparable. As a result, transportation departments have to fully rely on statements made by their vendors.

The Idaho Transportation Department has many RWIS stations across the state. According to the vendor of the infrared temperature sensors installed at these stations, the measurement area of the sensor has an approximate diameter of 80 cm at a distance of 10 m and the diameter changes proportionately by distance. The experiment reported in this paper was designed to test that assertion. Based on the results reported here, the vendor's suggestion of an 80 cm diameter for a distance 10 m was somewhat accurate in a lab setting but grossly inaccurate in the field. The size of the area that the sensor detects in the field was found to be more than double that suggested by the vendor. Therefore, it is recommended that independent verifications of such vendor statements be made.

As noted during a Transportation Research Board conference [11], there is a need to think strategically about the development of remote sensing in transportation. The recommendations made at the conference with respect to wide-area remote sensing regarding the adoption of a model similar to the Intelligent Transportation Systems model of national protocols, architecture, and standards, are also applicable to RWIS systems. Therefore, it is recommended that departments of transportation at the state and federal levels should take steps towards standardizing field and test procedures for RWIS sensors.

Before such standardized procedures are developed, it is recommended that state departments of transportation follow the field procedure described in this paper to estimate the footprint of road temperature sensors prior to using alternative means of temperature measurements to verify the accuracy of their sensors.

Acknowledgement

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Biographies

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