Study of LTPP Pavement Temperatures

PUBLICATION NO. FHWA-RD-02-071 MARCH 2005

U.S. Department of Transportation
Federal Highway Administration

Research, Development, and Technology
Turner-Fairbank Highway Research Center
6300 Georgetown Pike
McLean, VA 22101-2296

FOREWORD

Since its inception, the Long-Term Pavement Performance (LTPP) program has been collecting temperature data from the General Pavement Studies (GPS) and Specific Pavement Studies (SPS) test sections. Temperature has a strong effect on pavement deflection test results, primarily in asphalt concrete, but also in portland cement concrete structures. Adjustment for temperature is made to deflection test results; and, for this reason, complete and accurate data on surface temperature and in-depth temperature of pavement structures are needed for future LTPP analysis and research. This study documents the first detailed review of the LTPP pavement temperature data elements. The report assesses the completeness and quality of the data, identifies anomalies in the data, and recommends remedial action for these anomalies.

T. Paul Teng, P.E.
Director, Office of Infrastructure
Research and Development

NOTICE

Quality Assurance Statement

Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
FHWA-RD-02-071		

4. Title and Subtitle	5. Report Date
Study of LTPP Pavement Temperatures	March 2005
	6. Performing Organization Code
7. Author(s) E.O. Lukanen, R.N. Stubstad, and M.L. Clevenson	**8. Performing Organization Report No.**
9. Performing Organization Name and Address Consulpav International P.O. Box 700 Oak View, California	**10. Work Unit No. (TRAIS)**
	11. Contract or Grant No. DTFH61-95-Z-00086
12. Sponsoring Agency Name and Address Office of Infrastructure R&D Federal Highway Administration 6300 Georgetown Pike McLean, VA 22101-2296	**13. Type of Report and Period Covered** Final Report October 1998 to November 1999
	14. Sponsoring Agency Code

15. Supplementary Notes

Contracting Officer's Technical Representative (COTR): Monte Symons, HRDI-13

16. Abstract

This study focuses on the quality of the pavement temperature data in the Long-Term Pavement Performance (LTPP) program. Reliable pavement temperature data are necessary in the research planned for the LTPP program. Pavement surface temperature measurements and in-depth pavement temperature measurements have been recorded since the beginning of the LTPP program. Until this study, these data have been subject to only broad checks established for individual fields; no additional quality checks were made. The LTPP database is now undergoing various quality investigations focusing on comparisons of the data from two independent sources—infrared surface temperature measurements that were recorded automatically and in-depth temperature measurements that were made manually. The comparative processes identified various data errors and errors in associated data elements such as the time measurement. Examples of such errors include data entry errors such as transposition of numbers and errors in the tens-place entries. Missing data, malfunctioning infrared sensors, and time-recording errors such as errors with time zone changes or daylight savings time changes were identified. All identified pavement temperature errors were submitted for further evaluation, which could lead to either corrections or removal of erroneous data from the LTPP database.

17. Key Words	18. Distribution Statement
Infrared temperature, pavement temperature, BELLS, FWD, falling weight deflectometer, LTPP, Long-Term Pavement Performance, temperature errors.	No restrictions. This document is available to the public through the National Technical Information Service, Springfield, VA 22161.

19. Security Classification (of this report)	20. Security Classification (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	33	

Form DOT F1700.7 (8-72) Reproduction of completed page authorized

SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
^oF	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	^oC
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
^oC	Celsius	1.8C+32	Fahrenheit	^oF
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.
(Revised March 2003)

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1. INTRODUCTION

BACKGROUND

Since its inception, the Long Term Pavement Performance (LTPP) program has been collecting temperature data from the General Pavement Studies (GPS) and Specific Pavement Studies (SPS) test sections. Temperature has a strong effect on pavement deflection test results, primarily in asphalt concrete (AC), but also in portland cement concrete (PCC) structures. Adjustment for temperature is made to deflection test results; and, for this reason, complete and accurate data on surface temperature and in-depth temperature of pavement structures are needed for future LTPP analysis and research. This study documents the first detailed review of the LTPP pavement temperature data elements. The report assesses the completeness and quality of the data, identifies anomalies in the data, and concludes with recommends for remedial action for these anomalies.

The stiffness, or modulus, of AC is extremely sensitive to temperature. Routine deflection test results usually are adjusted to represent the deflection at a standard temperature or some other reference temperature, or the back-calculated modulus must be adjusted to the modulus expected at some selected seasonal temperature. Several procedures have been developed to adjust for temperature; however, most of these have been based on limited data.

Although the stiffness, or modulus, of PCC is not as temperature sensitive, the deflections measured on jointed PCC pavements are affected by the temperature gradient present in the slab because of “curling” and “warping” effects. Generally, curling occurs during nighttime and early morning when the temperature gradient in the PCC is positive from top to bottom (warmer at the bottom). Warping generally occurs between late morning and early evening when the temperature gradient in the PCC is negative from top to bottom (warmer at the top from solar radiation). The PCC temperatures also have a major effect on joint load transfer because of thermal expansion or contraction of the concrete panels and the corresponding effect on joint openings.

For these reasons, it is important that the Information Management System (IMS) contain correct and useable pavement temperature data. The temperature dataset generally has been collected in the Long Term Pavement Performance (LTPP) program according to protocols established for pavement monitoring. LTPP temperature measurements generally are conducted in conjunction with falling-weight deflectometer (FWD) deflection testing. Three procedures are used to measure pavement temperature:

- Infrared (IR) sensors mounted on a FWD measure surface temperatures. One temperature reading is made through the FWD’s automated software at each deflection test location.

- Manual in-depth pavement temperature measurements from holes drilled at each end of the test section to specified depths in the pavement. The in-depth temperatures are measured manually with a hand-held digital thermometer. The digital thermometer has a probe that is placed in the bottom of each hole. A small amount of heat transfer liquid (mineral oil or glycol) is placed in the bottom of the hole to transfer the pavement temperature to the probe.

- For selected Seasonal Monitoring Program (SMP) sections, permanent placement of thermistors at pavement subgrade. Onsite data loggers read the temperature from each of the thermistors and record the average temperatures hourly. Data from the SMP provides more detailed information on daily and seasonal variations in pavement temperatures.

It is difficult to distinguish how well or poorly the three temperature measurements correlate with one another, which one produces the most accurate data, or what the degree of variation is among the three methods.

OBJECTIVES

The principal objective of this study is to provide the best data possible for future LTPP analysis and research. The study attempted to estimate the precision and bias of the temperature measurement variables.

METHODOLOGY

The data that have been uploaded into Level E of the Information Management System (IMS) database have passed broad screening criteria. For this project, we evaluated for comparative reasonableness all of the manual and IR temperature data that have reached Level E. For example, a number of fields that contain numbers and temperatures should fall within a reasonable range. The quality control range listed in the data dictionary for the manual temperature is -11.1 °C to 50 °C (12 °F to 122 °F). We evaluated the data for errors, biases, and missing observations.

The following paragraphs provide more detail on the three pavement temperature measurement methods.

Infrared Surface Pavement Temperature

As part of the deflection testing process, an IR temperature sensor measures the temperature of the surface of the pavement under the FWD at the end of each test sequence. The FWD computer automatically records the information. Associated information includes the site number, date of test, and time of test. The FWD field data files are returned to the regional coordination office where the files are filtered into the IMS using FWDSCAN, a quality control software used to check the FWD data for completeness and readability.

Manual In-Depth Pavement Temperatures

Temperatures are measured at two locations, generally about a meter before and after the test section. The temperature measuring protocol is contained in the FWD field operation manual.[1] Holes are drilled in the pavement to depths of 25 mm below the surface, at mid depth, and 25 mm above the bottom of the asphalt or concrete. In composite sections, the three depths apply to the concrete, and two additional holes are placed to get asphalt temperatures at 25 mm from the top and bottom of the asphalt overlay. Heat transfer fluid is placed in the bottom of each hole, and a tip-reading temperature probe is placed into the liquid (about 10 mm to 12 mm of mineral oil or glycol to prevent evaporative cooling and freezing). The temperature is read with a digital thermometer that displays the temperature to a resolution of -18 °C (0 °F). The temperatures are measured about every half hour and hand recorded on a form, along with information about the station and site number, time and date of the measurement, depth of the hole, and the sky cover. The data on forms are recorded manually in the database in the regional coordination office.

Seasonal Monitoring Program Pavement Temperatures

All Seasonal Monitoring Program (SMP) sites are fitted with temperature, moisture, and weather instrumentation.[2] The temperature instrumentation in the pavement consists of 300-mm stainless steel tubes or rods fitted with three thermistors, one at each end and one in the middle. The rods, which are placed in slots cut into the pavement, are angled so that the top of the rod is 25 mm below the surface and the bottom of the rod is 25 mm above the bottom of the asphalt or concrete. A data logger monitors the thermistors and the weather instruments, reading the thermistors every minute. A data logger records the average hourly reading at the end of each hour. While the thermistor data are not time-specific, they do provide a good characterization of the diurnal and seasonal temperature variations. A review of the thermistor data was a lower priority for this project because these data already are evaluated as part of the SMP data screening and filtering. The thermistor data for the first two rounds of SMP testing were compared with both the manual and IR data by Lukanen et. al.[3] in an earlier study.

REPORT OVERVIEW

Chapter 2, “Data Extraction and Processing,” describes the data fields used and how the data were evaluated. Chapter 3, “Errors Found and Responses,” describes the type of errors found and the extent of the errors by error type. Chapter 4, “Recommendations,” offers recommendations for the correction of data errors and minimization of such errors in the future.

CHAPTER 2. DATA EXTRACTION AND PROCESSING

The approach to evaluating the quality of the manual and infrared temperature data was to compare the data sets and individual data elements to previous and subsequent data elements. Two forms of temperature measurements are available for the comparison—(1) infrared surface pavement data from table MON_DEFL_LOC_INFO (M04) and (2) manual in-depth pavement data from tables MON_DEFL_TEMP_DEPTHS (M21) and MON_DEFL_TEMP_VALUES (M22). The two sets of data, IR and manual, are then compared to each another. The calibration settings for the infrared sensors are contained in the table MON_DEFL_DEV_CONFIG (M02). The data fields used for the project are listed in the Appendix.

DATA FILES

The dataset that had reached "Level E" status was furnished on CD-ROM in ASCII format. The temperature data and other relevant data were extracted from the tables and assembled into individual section files, uniquely identified by STATE_CODE and SHRP_ID. The infrared and manual temperature data were merged into various files, one for each section, called SITESM files. The data in these files are sorted by date and time of test. Three additional data fields were included in these files, one calculated field for the infrared temperature based on the manufacturer's default factory calibration factors, one for the manufacturer of the infrared sensor, Williamson (W) or Raytec (R), and one for the previous day's average air temperature, provided by an FHWA data contractor for all the GPS sites. (The previous day's air temperature can be used to predict temperatures in the pavement based on the BELLS2 prediction model.) During the assembly of each of these files, an interpolated infrared surface temperature was calculated for each manual temperature record using standard linear interpolation (or extrapolation) methods. The extrapolated values were less reliable.

IR CALIBRATION

The infrared sensors used on the FWDs generate an electrical response that is converted to an electrical potential (in millivolts), which is linearly related to the surface temperature of the pavement. The two IR devices each have two default millivolt (mV) values that correspond to the sensor output when the pavement surface temperature is 0 °C and 100 °C. Table 1 contains the default calibration values for the two types of sensors used.

Table 1. Default calibration values for the two sensors used.

Manufacturer	Output at 0 °C	Output at 100 °C
Williamson	800 mV	2080 mV
Raytec	1300 mV	4200 mV

These default values are included in the header file of the FWD field program, which uses these values to linearly interpolate (or extrapolate) the IR sensor response to the surface temperature. Figure 1 gives the equation to convert millivolts to temperature.

$$T = 100\frac{mV - Cal_0}{Cal_{100} - Cal_0}$$

Figure 1. Equation. Converting millivolts to temperature.

For example, if the output from the Williamson sensor is 1440 mV (half way between 800 and 2080 mV), the surface temperature is 50 °C.

LTPP protocol for the FWD required periodic calibrations of the IR sensors. A water-and-ice mixture was used for a 0 °C reference, and nearly boiling water was the hot temperature reference. (Boiling water as a 100 °C reference proved to be impossible to use for calibration because of the interference of the steam and different emissivity.)

The process of calculating the default IR values is to use the equation in figure 1 and calculate the actual IR sensor output in millivolts. Using IMS data field names, figure 2 gives the equation in figure 1 solved for millivolts.

$$mV = \frac{PVMT\_SURF\_TEMP(PVMT\_SENSOR\_VOLTAGE\_100C - PVMT\_SENSOR\_VOLTAGE\_0C)}{100} + PVMT\_SENSOR\_VOLTAGE\_0C$$

Figure 2. Equation. Calculate default IR values to derive IR sensor output in millivolts.

The three requisite input variables to this equation are available in the data tables. After the millivolt value is calculated from the equation above, the factory default calibration values and the millivolt output are used in the equation in figure 1 to calculate the default IR reading for T. This procedure was done for all of the data evaluated, and the calculated default IR (D.IR) values are included as a separate field in the combined files.

IR Calibration Issues

Lukanen et. al.,[3] in a previous LTPP project found some significant differences between the various infrared sensors mounted on the various LTPP FWDs. The calibration protocols resulted in more variation from sensor to sensor than would result if the factory calibrations had been used. As a result of these findings, the infrared readings, as calibrated by the regions, and the manufacturers' default calibrated infrared readings were regressed against the measurements in the LAYER_TEMPERATURE1 field. The results for the North Atlantic and Western Regions appear in tables 2 and 3. (LAYER_TEMPERATURE1 is typically measured in a 25-mm deep hole with 5 mm to 10 mm heat transfer fluid at the bottom of the hole.) The manufacturers' calibrations resulted in more consistency from year to year and sensor to sensor.

Table 2. Regression statistics for infrared versus manual temperatures from the North Atlantic Region.

				Mfg. Calibrated Infrared Sensors					**Regional Calibrated Infrared Sensors**			
Unit	Start	End	Records	Intercept	Slope	R^2	S.E.E.	Mfg.	Intercept	Slope	R^2	S.E.E.
058A	7-Dec-88	17-Nov-89	895	3.840	0.803	0.945	1.949	W	4.318	0.793	0.945	1.948
058B	21-Feb-90	7-May-92	537	4.182	0.777	0.888	2.855	W	3.920	0.691	0.888	2.854
058C	19-Feb-92	23-Aug-95	461	0.601	0.843	0.961	2.332	W	0.601	0.843	0.961	2.332
058D	22-Mar-94	9-Dec-94	234	0.585	0.827	0.953	1.830	W	7.349	0.765	0.953	1.829
058E	17-Jan-95	12-Jul-95	130	-0.917	0.908	0.980	1.735	W	4.983	0.626	0.980	1.733
			Average =	1.658	0.832	0.945	2.140		4.234	0.744	0.945	2.139
			Std.Dev. =	2.238	0.050	0.035	0.459		2.427	0.086	0.035	0.460
058H	11-Sep-95	8-Jul-98	966	2.181	0.883	0.955	2.270	R	2.182	0.883	0.955	2.270
129A	21-Mar-94	22-Jun-95	572	1.420	0.898	0.955	2.280	R	0.509	0.914	0.955	2.282
129D	5-Sep-95	15-Jul-98	933	2.273	0.843	0.952	2.336	R	2.724	0.796	0.952	2.332
			Average =	1.958	0.875	0.954	2.295		1.805	0.864	0.954	2.294
			Std.Dev. =	0.468	0.029	0.002	0.035		1.155	0.061	0.002	0.033

Table 3. Regression statistics for infrared versus manual temperatures from the Western Region.

				Default Factory Calibration					**Region Calibrated**			
Unit	Start	End	Records	Intercept	Slope	R^2	S.E.E.	Mfg.	Intercept	Slope	R^2	S.E.E.
061G	26-Feb-89	29-Jan-90	752	2.785	0.867	0.883	2.745	W	9.168	0.422	0.883	2.743
061F	3-May-90	30-Oct-90	40	3.661	0.942	0.963	2.283	W	8.314	0.680	0.963	2.292
061E	17-Feb-95	31-Mar-95	118	-2.418	0.937	0.923	1.612	W	1.420	0.799	0.922	1.615
061D	29-Apr-91	26-May-93	622	3.715	0.852	0.953	2.482	W	5.367	0.749	0.953	2.479
061C	24-Jun-93	11-Mar-94	74	2.963	0.858	0.966	2.470	W	3.553	0.755	0.966	2.465
061B	6-Dec-90	14-Dec-94	275	-0.723	0.875	0.948	1.874	W	-0.723	0.875	0.948	1.874
061A	15-Jan-91	16-Apr-91	41	6.159	0.758	0.760	3.792	W	7.748	0.606	0.569	5.081
001A	12-Jul-93	5-Apr-94	123	3.666	0.858	0.948	2.205	W	4.877	0.702	0.948	2.211
			Average =	2.476	0.868	0.918	2.433		4.965	0.698	0.894	2.595
			Std.Dev. =	2.737	0.057	0.069	0.656		3.458	0.138	0.134	1.066
131D	11-Aug-96	30-Mar-98	772	3.588	0.855	0.951	2.274	R	3.685	0.787	0.952	2.270
131C	7-Apr-98	5-Oct-98	290	4.187	0.890	0.948	1.925	R	3.790	0.809	0.948	1.925
131B	24-May-94	31-Jul-96	677	2.988	0.902	0.969	2.215	R	2.240	1.105	0.969	2.215
131A	13-Jan-95	24-May-95	179	1.185	0.940	0.942	2.144	R	-1.172	0.782	0.942	2.140
	17-Jul-95	19-Aug-98	1283	2.375	0.872	0.934	2.918	R	1.724	0.813	0.934	2.919
			Average =	2.865	0.892	0.949	2.295		2.053	0.859	0.949	2.294
			Std.Dev. =	1.156	0.032	0.013	0.373		2.014	0.138	0.013	0.373

Comparing the manual and infrared temperatures provides a means to scan for errors. For example, the small crosses in figure 3 are D_IR pavement surface readings; the circles are the manually measured temperatures at about 25 mm below the pavement surface for one of the LTPP FWDs. The plot shows that the IR sensor did not work well during the winter, and it became erratic after May 24, 1995. For each of the IR calibration periods, the comparisons were used either to find times when the equipment malfunctioned or to find errors in the upper manual measurements at 25 mm depth.

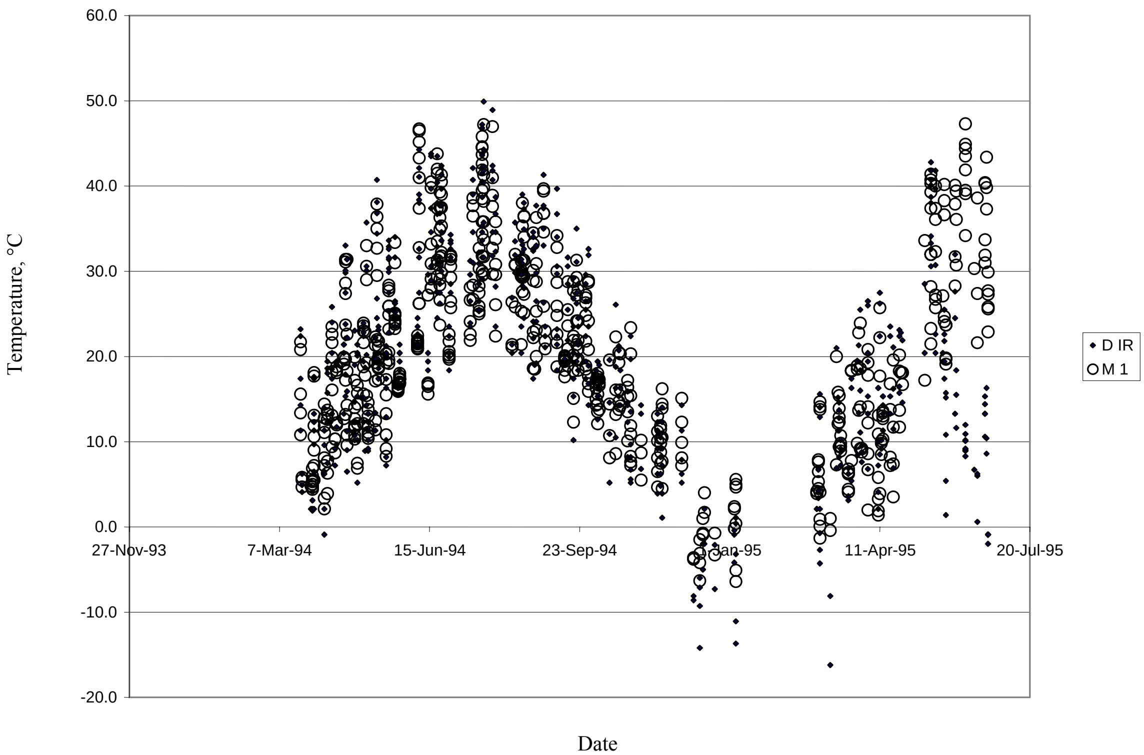

Figure 3. Graph. Infrared and manual temperatures for SN 8002-129.

A key premise to this exercise is the idea that the manual temperature is considered to be the best representation of the pavement temperature. The temperature meters and probes that measure the temperature in the heat transfer liquid placed at the bottom of each manual temperature measurement hole were not subject to any rigorous calibration or verification. The manufacturer's specifications and certifications for the meters were accepted as statements of their accuracy; however, it is easy enough to check the probes and meters against reference thermometers that are traceable to the National Institute of Standards and Technology (NIST).

Two models of infrared sensors were used over the course of the LTPP project. The initial IR sensors were manufactured by Williamson. The first set of four FWDs were SHRP FWDs. A second set of four FWDs was delivered in 1995, one to each of the Regions. These machines were equipped with Raytec sensors. During the summer of 1995, the original Williamson sensors were replaced with Raytec sensors. It was also found that the factory default calibration settings for the Raytec sensors were more consistent from sensor to sensor than the calibration settings for the Williamson sensors. The Williamson IR sensors tended to correlate well (although not necessarily one-to-one) with the manually measured pavement temperatures on a case-by-case basis; however, there were significant differences from one IR sensor to the next. The Raytec IR sensors were more consistent from sensor to sensor. The regression results shown in tables 2 and 3 confirmed the earlier findings.

Post-Testing of Infrared Calibration Constants

The temperature measurements conducted in LTPP make it possible to consider post-testing calibration of the infrared sensors. If we accept the manual temperatures as a reliable temperature reference, we can use the shallow manual temperatures and the regression results shown in tables 2 and 3 to calculate a new set of calibration factors for 0 °C and 100 °C. This process also requires the selection of a reference intercept and slope. The weighted average of the slope and intercept for the more reliable Raytec sensors, for example, could be used as the reference relationship between the IR sensors and the top manual temperatures. The equation form in figure 4 shows the relationships reported in tables 2 and 3.

$$M_1 = a + b * IR$$

Figure 4. Equation. Relationships in Tables 2 and 3.

Replacing the IR term with the equation shown in figure 1, the equation in figure 4 can be rewritten as shown in figure 5, where *a* is the intercept and *b* is the slope.

$$M_1 = a + \frac{100 * b * mV}{Cal_{100} - Cal_0} - \frac{100 * b * Cal_0}{Cal_{100} - Cal_0}$$

Figure 5. Equation. Rewritten Figure 4 equation to replace IR term.

Converting $Cal_{100} - Cal_0$ to Cal_Δ and $M_1 - a$ to M′, the equation can then be rewritten as shown in figure 6.

$$M' = \frac{-100 * b * Cal_0}{Cal_\Delta} + \frac{100 * b}{Cal_\Delta} * mV$$

Figure 6. Equation. Using conversion equation to rewrite equation.

By using the two calculated variables, M′ as the dependant variable and mV as the independent variable, all of the output for any of the sensors and dates can be regressed. The new regression intercept would be $(-100*b*Cal_0) / (Cal_\Delta)$ and the slope would be $(100*b) / (Cal_\Delta)$, yielding two equations with two unknowns. Cal_Δ can be calculated by $Cal_\Delta = (100*b) / \text{slope}$. Cal_0 can be calculated by $Cal_0 = (\text{Int.} * Cal_\Delta) / (-100*b)$. This process can be applied to each individual calibration period for the Williamson IR sensors—and to a Raytec IR sensor, for that matter, if it correlates well with $M_{1,}$ but it has significantly different regression coefficients.

Applying this process to the IR sensor on FWD S/N 058A results in a new set of calibration factors, of 778.98 and 2,122.85 for Cal_0 and Cal_{100} respectively. Using the new calibration factors, a new set of computed values (abbreviated in tabular form as "C.IR") can be developed.

PLOT SCANNING

The method used to search for errors that was most productive was to manually view time plots of the temperatures measured on a given section for individual test days. This search was automated by using a spreadsheet macro to allow rapid review of the plots of the data by simply clicking on a "spinner bar" to step forward or backwards through the sections, day by day. There was too much variation in the temperatures caused by factors such as cloud cover, rain, or shadow effects. These variations made automated screening of the data with preset or data-determined numerical criteria difficult.

An example of an error is provided by the plot in figure 7. The plot shows two sets of manual temperature data, reportedly from the same site and day of test. One set of data indicates a warmer surface and one shows a cooler surface. The erratic IR plot is from two individual sets of data that are superimposed on the same time scale. Clearly, one set of manual data and one set of IR data are incorrect. In all likelihood, the two sets of data are not from the same LTPP site.

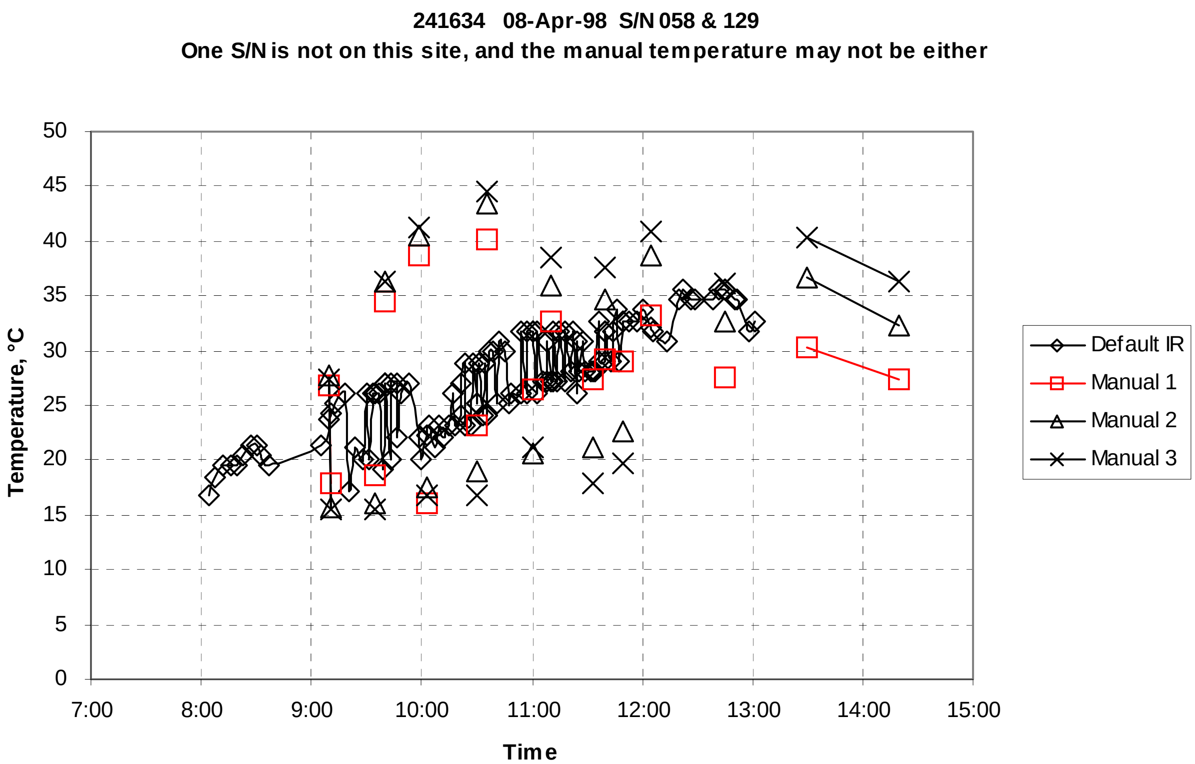

Figure 7. Graph. Example of time plot of temperatures.

CHAPTER 3. ERRORS FOUND AND RESPONSE

This chapter is divided into the types of errors found using the temperature plot scanning procedure and variations of errors within the types.

IRRELEVANT IR TEMPERATURES

Many of the records in the M04 tables, for the testing on SPS-1, SPS-2, and SPS-8 projects, have entries in the PVMT_SURF_TEMP field when the tests were on the subgrade, granular base, lean concrete (lean PCC), or permeable asphalt treated base (PATB); therefore, many data are likely to be incorrect. The IR data on subgrade and granular base are not relevant, and all should be replaced with nulls. A determination should be made regarding the relevance of the temperatures that are available on lean PCC and PATB.

FWDs WITHOUT AN IR SENSOR

Some testing was done with an FWD equipped with an IR sensor that was either missing or not working. In either case, the filter program that processes the field files into the database reads the blank field as a zero ("0"), a reading that is incorrect. In addition, the filter program should be modified to check for lane designations—"S" (subgrade), "G"(granular base), "L" (lean PCC), and "P" (PATB). All these records should have the value in the PVMT_SURF_TEMP field replaced with a null or blank field.

FWDs without IR sensors typically exhibited nonsensical values in the header file for calibration numbers, in PVMT_SENSOR_VOLTAGE_0C and PVMT_SENSOR_VOLTAGE_100C fields of the M02 tables. The M04 tables can be searched for the records that correspond to configurations that have nonsensical values. These cases will be easy to identify. These records should then be evaluated because some FWD operators were able to enter surface temperatures from a hand-held IR thermometer. Records that did not have IR sensors were identified during the temperature plot scans rather than the above-described method. This can be easily written into the FWD filter program and also used as an independent check for bad IR data.

Table 4 lists examples of sites where IR data were in the database, but the data were not valid. These cases are a sample of such cases for Region 2. Note that these may not include all of the data; they are only part of the data for the day. An example is Section 271028 on May 10, 1994, where the IR stopped working after the test at 13:45, as shown in the example in figure 8.

Table 4. Examples of invalid site data.

ID	State	Const. No.	Date	IR	Man	Unit SN	Comment
1010	20	1	Jan.15, 1992	N	Y	8002-060	Ptly Cloudy, cold, IR not functioning
1005	20	1	Feb.19, 1992	N	Y	8002-060	Cloudy, Cold, IR all 0s; remove
1005	20	1	Feb.20, 1992	N	Y	8002-060	Sunny, IR all 0s; remove
1009	20	1	Feb.21, 1992	N	Y	8002-060	IR not working; remove data
1010	20	1	Feb.25, 1992	N	Y	8002-060	IR data is there, but no sensor; remove data
1028	27	1	May 10, 1994	N	Y	8002-060	IR values after 13:45 are ~ 0° and not valid; remove
1028	27	1	June 14,1994	N	Y	8002-060	IR values of 0° not valid; remove
1018	27	2	Jan.9,1995	N	Y	8002-060	IR data should have been null or empty, not zeros

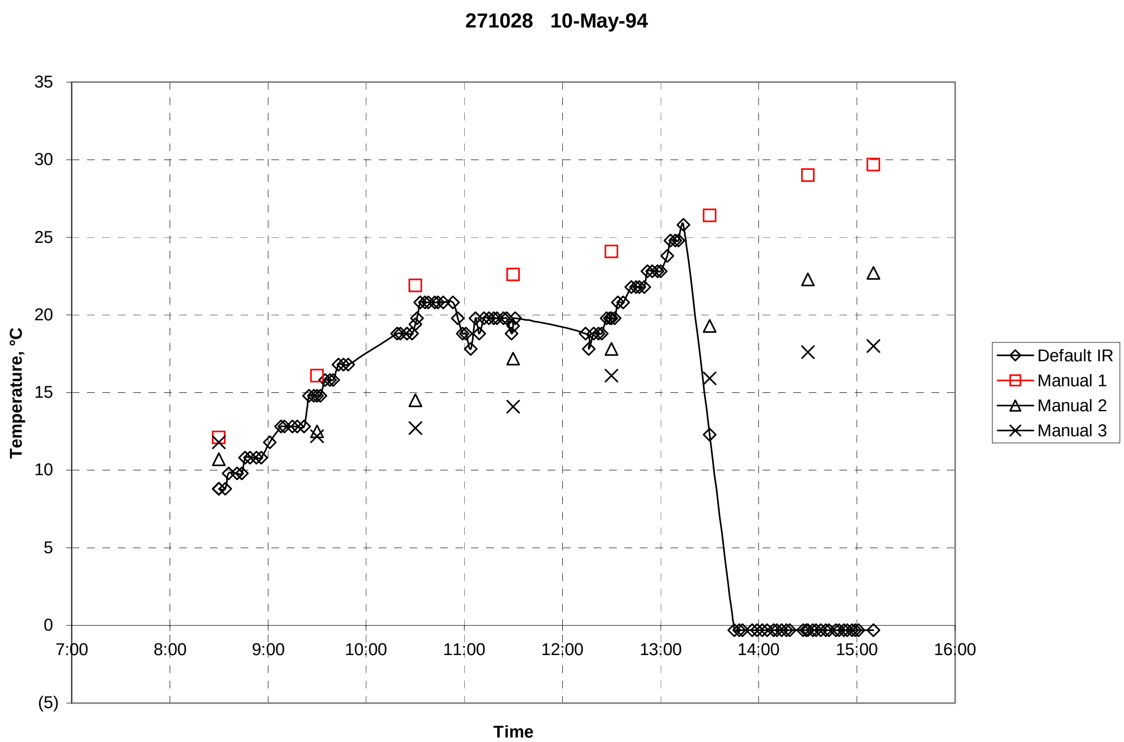

Figure 8. Graph. Example of an IR sensor ceasing to function.

TIME ENTRY ERRORS

A number of sections have errors in time entry. They come in a variety of forms, including the time of the manual measurement; time zone time errors for either the manual recordings or FWD computer time, or both; daylight savings time errors; or simple data recording or entry errors.

Time of Manual Measurement

The most noticeable form of this error is recording and entering a manual temperature measurement that was made in the afternoon as the time based on a 12-hour clock, such as recording 13:00 as 1:00. These errors, found while scanning the daily temperature plots, were readily noticeable. Screening of manual temperature times recorded between midnight and 6 a.m. would catch most of these errors. Some caution is advised because some testing in Region 4 was at night.

Incorrect Computer Clock Setting

This data entry error, caused by setting the computer clock in the afternoon on 12-hour time instead of 24-hour time, resulted in deflection time stamps that are 12 hours late. In addition, date errors occurred if the first error was not corrected by the next morning. Figures 9 and 10 show examples of such errors, with the additional complication in figure 9 that the shift occurred from 9:00 to 21:00 rather than at noon as shown in figure 10.

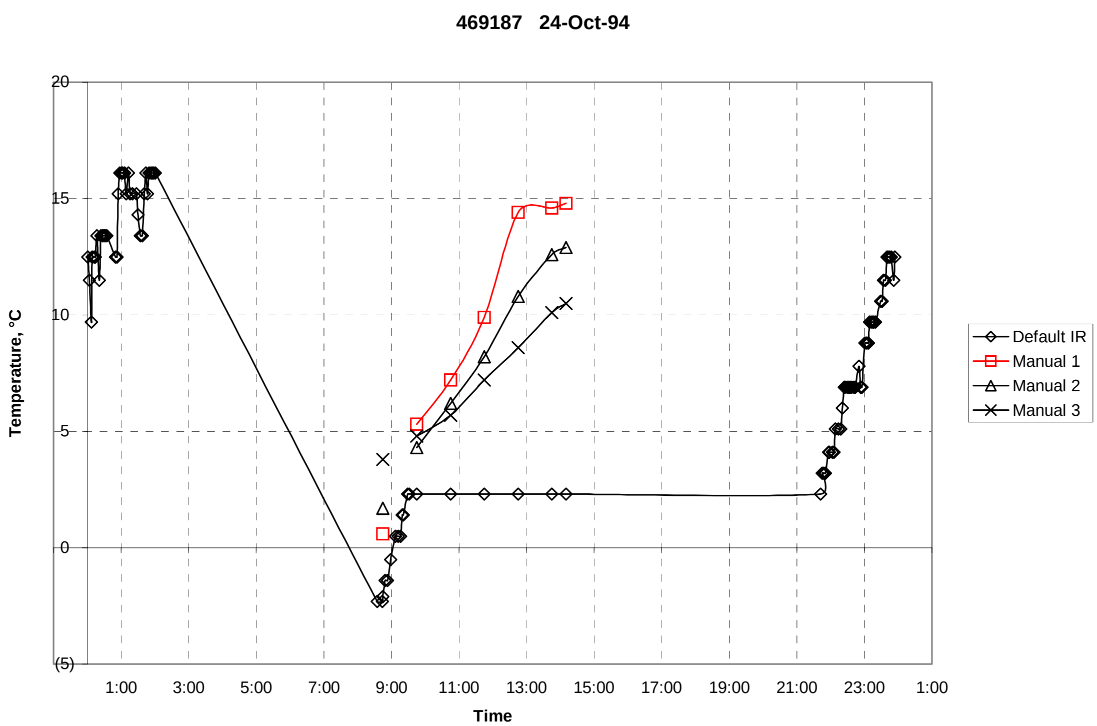

Figure 9. Graph. Time-temperature plot showing computer time error.

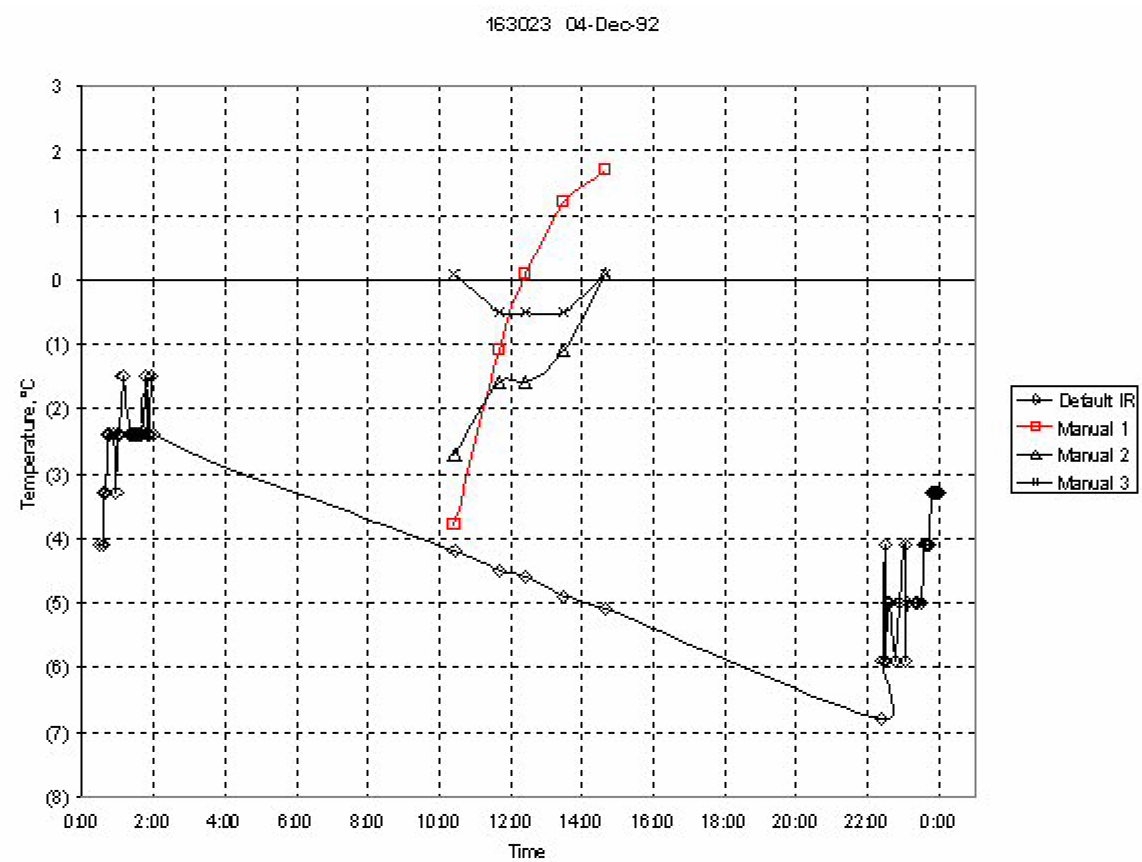

Figure 10. Graph. Time-temperature plot showing 12-hour computer time error.

Time Zone Errors

This error could have occurred when the time of the manual temperature measurement was recorded if the operator did not account for crossing a time zone, or if the operator did not adjust the computer clock for the time zone change. If the operator did not account for the time zone change in the computer or adjust for it while recording the manual temperatures, the error generally is undetectable. This error probably is not too serious because it likely is consistent with the rest of the data.

Daylight Savings Time Errors

These errors are similar to time zone errors, except they occurred only during the first few weeks of April or the first few weeks of November. As with time zone errors, if both the manual and FWD times go unadjusted, the error is not easily detectable and probably is not too serious because it likely will be consistent with the rest of the data.

Double entries of FWD data can occur with either the time zone or daylight savings time errors if the region filters the data into IMS, recognizes the problem, edits the field files to correct the time, and then refilters the FWD file into the database without removing the initial entry. Occurrences of this error were found during both the temperature scans and deflection checks. (Deflection checks are a separate process that is not covered in this report.) For the most part, this problem has been identified and the Region must now review the data to determine which set is correct and corresponds to the deflection data set as corrected and reported previously.

Simple Time Recording and Entry Errors

These errors are found during scanning of the time temperature plots as misplaced times. If the error is large enough and there is sufficient temperature change, incorrectly recorded or entered time will stand out. Suspect data can be identified, but it requires that the region review the data sheets and make appropriate corrections.

TEMPERATURE ERRORS

There are a number of temperature data recording or entry errors. Errors such as transposing the numbers, incorrectly entering the tens-place value, and reversing the temperature holes were identified by visually scanning the time-temperature plots. These errors can be expected; and as expected, they did occur. If the errors are sufficiently large, they can be detected by observing the plots, as shown in figure 11. Generally, the smallest detectable error is -12 °C (10 °F), as shown in figure 12. Note that the LTPP protocol required the temperature measurements to be in Fahrenheit.

An alternative process that could be used to search for temperature errors is to use the BELLS2 method to estimate the temperature at the depth used in the database. This procedure could be used for all flexible pavements where the previous day’s average air temperature data are available. The IR calibration problems described earlier first need to be resolved. Then the IR temperatures can be used to estimate in-depth temperatures, which, in turn, can be compared to the measured temperatures. That process might detect errors smaller than those identified in visual scans; however, this is uncertain.

The BELLS2 equation can also be compared to temperatures in rigid pavements. Preliminary calculations (before data cleaning) were carried out for both surface types (AC and PCC), and the results were encouraging. Figures 13 and 14 show the results for FWD SN 8002-058 while equipped with a Raytec IR sensor. Note that there are many outliers that may be a result of data problems such as infrared extrapolations and manual temperature data errors. As seen, the data band in figure 13 is much tighter than in figure 14; figure 13 data is for manual 1 data, generally from about 25 mm below the surface, and figure 14 is from manual 3, which generally are 25 mm above the bottom of the bound layer, and therefore, more likely to have greater variation. The adaptation of BELLS2 (or BELLS3) to PCC surfaces could be developed from this data and would be another LTPP product. Time was insufficient to complete that as part of this project, but the concept has been tested with encouraging results.

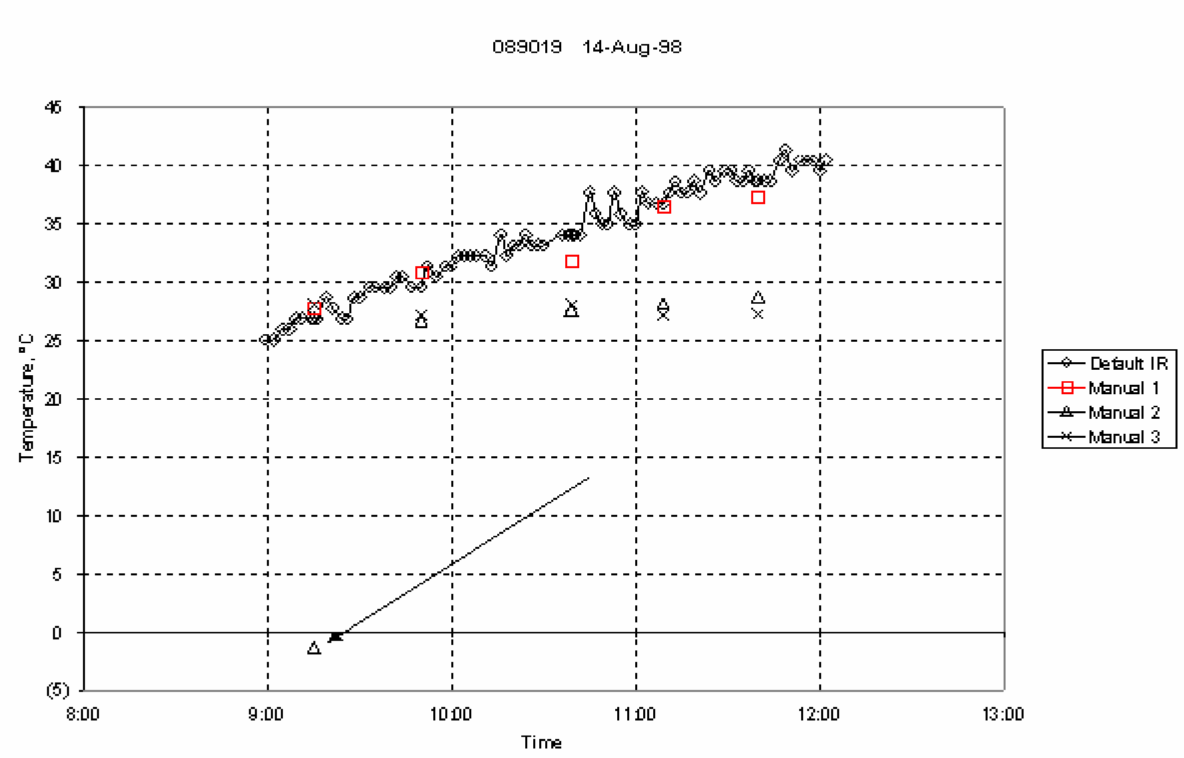

Figure 11. Graph. BELLS2 prediction for manual 1 temperatures using default IR data before cleaning.

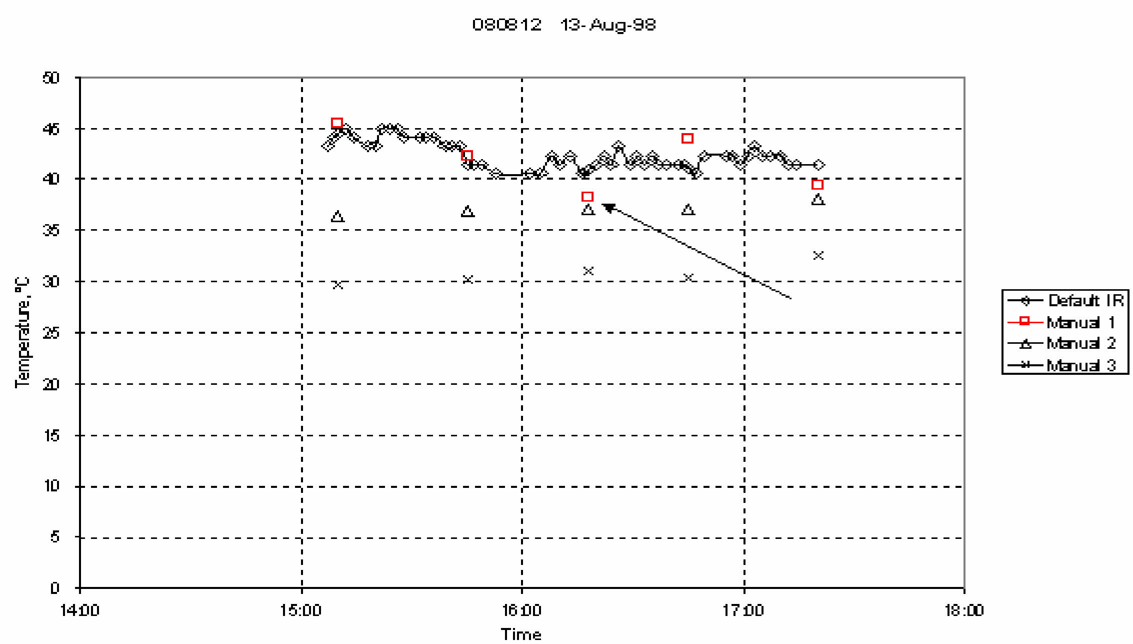

Figure 12. Graph. Minimum detectable error possible by visual scan.

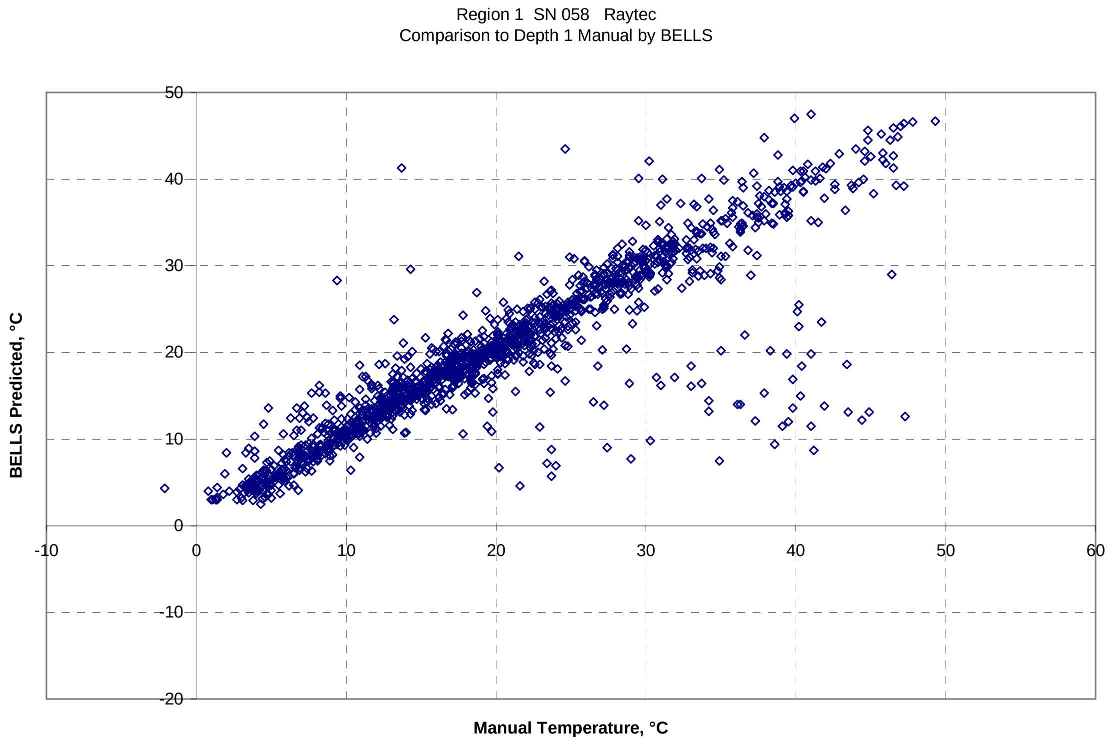

Figure 13. Graph. Manual 1 and BELLS2 compared (before data cleaning; all surfaces).

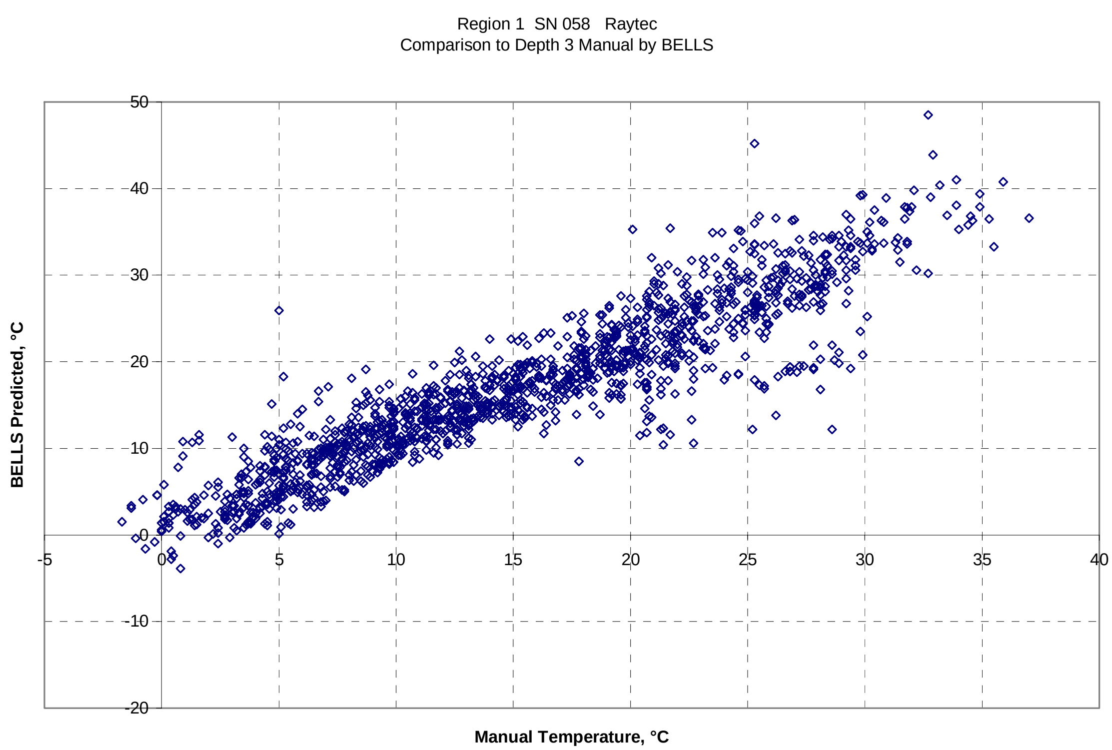

Figure 14. Graph. Manual 3 and BELLS2 compared (before data cleaning; all surfaces).

SUMMARY OF ERRORS DETECTED BY REGION

The temperature data were scanned by Region, one date at a time. Because of time and budget restraints, the scanning was complete for only Regions 2 and 4, and about 75 percent complete in Region 1. Region 3 temperature data were not scanned at the time this report was prepared. In Regions 2, 3, and 4, where SPS-1 and SPS-2 testing was done on the subgrade (S), granular base (G), permeable asphalt treated base (P), or lean concrete base (L), no manual temperature measurements were made on these surfaces. Following is a list of the number of individual section-days available for scanning:

- Region 1: 1,247 section-days—total includes no P, L, S, or G section-days.
- Region 2: 1,995 section-days—including 12 P, 4 L, 41 S & 20 G section-days.
- Region 3: 2,188 section-days—including 0 P & L, 24 S & 13 G section-days.
- Region 4: 2,078 section-days—including 21 P, 3 L, 92 S & 41 G section-days.

Region 2

The following paragraphs summarize the Region 2 temperature problems found in scanning the plots.

Sections with Missing Temperature Data. In all of the sections of test data in Region 2 that have reached Level E, the sections shown in table 5 have no temperature data. An approximation of pavement temperatures could be made based on historic climatic data specific to this SPS-5 site or similar sites nearby and other test dates with IR and manual temperature. These approximations (predictions) come within about ±5 °C. Other sections also have missing data in the IMS.

Table 5. Region 2 FWD data without IR and manual temperature data.

ID	State	Date	SN
501	27	July 20, 1990	8002-005
507	27	July 20, 1990	8002-005
504	27	July 21, 1990	8002-005
506	27	July 21, 1990	8002-005
505	27	July 22, 1990	8002-005
509	27	July 22, 1990	8002-005
502	27	July 23, 1990	8002-005
503	27	July 23, 1990	8002-005
508	27	July 23, 1990	8002-005

Sections with Missing Manual Data. There could be several reasons why a section has no manual data:

- Testing was on subgrade, granular base, PATB, or lean concrete; manual temperature measurements are not required for these surface types.
- Manual temperatures were not measured.

- Manual temperatures were measured but not entered into the database.
- Manual temperatures have not advanced to Level E.
- Minnesota Test Road (MnROAD) GPS sections—manual temperatures were not measured. All of the sections at MnROAD were instrumented with thermocouples. The temperature data from MnROAD need to be transferred into the IMS, or users need to be directed to where the data is available on the MnROAD web site.

The first group consists of tests conducted on SPS-1, SPS-2, or SPS-8 during construction. These sections did not require manual data because the tests were conducted either on subgrade, granular base, or PATB; however, some of these sections did have IR data. The IR data were not screened and no assessment is given as to the validity of these data. It may be important to screen the PATB data because the deflections on this material are temperature dependent. Manual temperatures were not made on PATB because of the permeability—any holes drilled in the material would not hold the requisite heat transfer fluid. It is recommended that the IR data on PATB be screened for suitability.

The next three groups cannot be individually identified at this time; however, sections with missing manual data are identified. A list of the sections with missing manual data should be submitted to the four Regions, which could then check their records to verify that the data are missing or that the data exist but have not been entered (in which case the data can be entered).

Sections that still do not have manual data, but do have IR data, could have a set of computed temperatures for the pavement based on the BELLS2 equation for asphalt surfaces. Concrete surfaced sections could be similarly treated following an evaluation of the BELLS2 equation for use on PCC surfaced pavements. The calculated temperatures could be approached in at least two ways:

- Apply BELLS2 to cleaned and calibrated IR data.
- Calculate the in-depth temperatures after calculating a new set of coefficients for the IR sensor and in-depth temperatures for specific calibration periods for each specific IR sensor. Using the new set of coefficients, calculate the in-depth temperatures for sections with missing data. Usually the best procedure to accomplish this is to use some weighting of site-specific estimated parameters with globally estimated parameters; we cannot identify these factors without further, more time-intensive analyses.

Sections with Apparent Manual Temperature Errors. Apparent manual temperature errors appear in 49 section-days; visual inspection of temperature plots makes the errors seem obvious. Of the 49 section-days, one has IR and manual data that are both suspect, and the rest have specific data elements identified as suspected errors. Identified errors should be checked by the Regions. A correction can be made when the error is an entry error. When the error may have been a recording or reading error, a decision must be made to either remove the data, leave it as is, or change the number to the expected value. A good method to handle the changed values is with computed parameters held in separate tables. On the other hand, separate tables could be cumbersome for researchers. To create the best set of data for researchers, it is possible to enter a separate data set containing both actual and computed data.

Section-Days With Possible Time Errors. There are 34 section-days with possible time errors. There are several ways time errors can be made**:**

- Recording afternoon times using a 12-hour clock system rather than the protocol 24-hour clock system. A time at 1 p.m. time, if entered as 1:00, is recorded in the database as 1:00 a.m.
- Not adjusting for going off or on daylight savings time in the computer clock or manual time recordings.
- Not adjusting, or incorrectly adjusting, for time zone changes.
- Filtering in FWD data twice, once with the original data, and once with the time adjusted. There are four section-day file cases of this.

Region 4

The following paragraphs summarize the Region 4 temperature problems caused by scanning the plots.

Sections with No Temperature Data. For all of the sections of test data that have reached Level E, the sections listed in table 6 have no temperature data at all. All of these sections are in Alaska; the temperatures for the first two sections probably were never measured, and the last three may not have been entered in time to be part of this analysis. An approximation of pavement temperatures could be made based on historic climatic data specific to these sites or similar sites nearby and other test dates with IR and manual temperature. These approximations (predictions) come within about ±5 °C.

Table 6. Region 4 FWD data without IR and manual temperature data.

ID	State	Date	SN
1008	2	Aug.21, 1989	800-002
1008	2	Aug.28, 1989	800-002
1004	2	Aug.20, 1997	800-003
1002	2	Aug.21, 1997	800-003
1001	2	Aug.22, 1997	800-003

Sections with Missing Manual Data. In Region 4, aside from the testing on the unbound layers, PATB, and lean PCC, manual temperature data are missing from 144 sections, not including all the SPS-3s and SPS-4s. Following is a list of grouped sections (sections here refer to section-days) missing manual temperature data:

- 43 flexible GPS sections.
- 14 rigid GPS sections—13 jointed and one of continuously reinforced concrete pavement (CRCP).
- 51 SPS-5 sections.
- 31 SPS-6 sections.
- 5 SPS-8 sections.
- All SPS-3 and SPS-4 sections.

There could be several reasons why these sections have no manual data:

- Manual temperatures were not measured.
- Manual temperatures were measured but were not entered into the database.
- Manual temperatures have not advanced to Level E.

The three groups could not be individually identified at the time of the study; however, it was possible to identify sections with missing manual data. A list of the sections with missing manual data should be submitted to the regions. The regions should then check their records to verify that the data are missing, or that the data exist but have not been entered, in which case the data can be entered.

Sections that still have no manual data, but that do have IR data, could have a set of computed temperatures for the pavement based on the BELLS2 equation for asphalt surfaces. Concrete surfaced sections could be similarly treated following an evaluation of the BELLS2 equation for use on PCC surfaced pavements. The calculated temperatures could be approached in at least two ways:

- Apply BELLS2 to cleaned and calibrated IR data.
- Calculate the in-depth temperatures after calculating a new set of coefficients for the IR sensor and in-depth temperatures for specific calibration periods for each specific IR sensor. Using the new set of coefficients, calculate the in-depth temperatures for sections with missing data. Usually the best procedure to accomplish this is to use some weighting of site-specific estimated parameters with globally estimated parameters; we cannot identify these factors without further, more time-intensive analyses.

Sections with Apparent Manual Temperature Errors. There are 82 section-days with apparent manual temperature errors. The errors seem obvious by visual inspection of temperature plots. These errors should be checked by the Region. In the case the error is a data entry error, a correction can be made. In case the error may have been a recording or reading error, a decision must be made to either remove the data, leave it as-is, or change the number to the expected value. Changed values may best be treated similar to computed parameters (i.e., they may be held in separate tables); however, this would be cumbersome for researchers. To create the best set of data for researchers, a separate data set that contains both actual and computed data should be made.

Section-Days with Possible Time Errors. There are 104 section-days with possible time errors. There are several ways time errors can be made:

- Recording afternoon times in the 12-hour clock method rather than 24-hour clock as per protocol. A 1:00 p.m. time, if entered as 1:00, is recorded in the database as 1:00 a.m.
- Not adjusting for going on or off daylight savings time in the computer clock or manual time recordings.
- Not adjusting, or incorrectly adjusting, for time zone changes.
- Filtering in FWD data twice, once with the original data and once with the time adjusted. There are four cases of this.

- Night testing where all the tests taken are listed for the day the testing was completed. For example, testing started at 22:00 or 10:00 p.m. and ended 2:00 a.m. The tests between 22:00 and midnight will be associated with the following day. This is a data filtering and field program operation problem.

The possible errors have been specifically identified and feedback reports will be submitted. This is an uncommon problem; no solution is offered at this time other than to manually edit the dates.

CHAPTER 4. RECOMMENDATIONS

There are no specific changes in temperature reading or recording protocol that are needed. Most of the errors are simple human errors. If anything, simple checks of reasonableness may help minimize data errors in the future. One method would be to devise a filtering process that would give a graphical view of the IR data, and allow the manual temperature data to be entered and displayed at the same time. Significant errors can be spotted in this way; this procedure is similar to the data screening carried out in this project.

One intra-module check could be added that would guard against having meaningless IR data for subgrade and granular surfaces, if any remain to be tested. The check could be worded as follows:

> If LANE_NO = S or G, then there should be no corresponding MON_DEFL_TEMP_DEPTHS and MON_DEFL_TEMP_VALUES records, and the PVMT_SURF_TEMP field in MON_DEFL_LOC_INFO should be null.

APPENDIX

Table	Field
M02	CONFIGURATION_NO
M02	PVMT_SENSOR_VOLTAGE_0C
M02	PVMT_SENSOR_VOLTAGE_100C
M04	SHRP_ID
M04	STATE_CODE
M04	CONSTRUCTION_NO
M04	TEST_DATE
M04	TEST_HOUR_MINUTE
M04	DEFL_UNIT_ID
M04	CONFIGURATION_NO
M04	POINT_LOC
M04	LANE_NO
M04	PVMT_SURF_TEMP
M04	AIR_TEMP
M04	COMMENTS_1
M04	COMMENTS_2
M01	OPERATOR
M21	SHRP_ID
M21	STATE_CODE

Table	Field
M21	CONSTRUCTION_NO
M21	TEMPERATURE_DATE
M21	LOCATION_NO
M21	DEPTH1
M21	DEPTH2
M21	DEPTH3
M21	DEPTH4
M21	DEPTH5
M22	SHRP_ID
M22	STATE_CODE
M22	CONSTRUCTION_NO
M22	TEMPERATURE_DATE
M22	LOCATION_NO
M22	TIME
M22	LAYER_TEMPERATURE1
M22	LAYER_TEMPERATURE2
M22	LAYER_TEMPERATURE3
M22	LAYER_TEMPERATURE4
M22	LAYER_TEMPERATURE5
M22	WEATHER_CONDITION

REFERENCES

1. Manual for FWD Testing in the Long-Term Pavement Performance Study: Operational Field Guidelines, Version 2.0, Federal Highway Administration, Pavement Performance Division, LTPP Division, February 1993.
2. *LTPP Seasonal Monitoring Program: Instrumentation Installation and Data Collection Guidelines*, FHWA-RD-94-110, McLean, VA: Federal Highway Administration, April 1994.
3. Lukanen, E.O., Stubstad, R., and Briggs, R., *Temperature Predictions and Adjustment Factors for Asphalt Pavements*, FHWA-RD-98-085, McLean, VA: Federal Highway Administration, June 2000.

HRDI-13/03-05(WEB)E