Study of Long-Term Pavement Performance (LTPP): Pavement Deflections

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LTPP

Foreword

Falling weight deflectometer (FWD) load-deflection data generally are used to characterize the tested pavement by an analysis of the applied load and the magnitudes (or shape) of the measured deflection basin. Often, these data are used to backcalculate layered elastic stiffnesses or moduli. The analysis results give the pavement researcher a measure of the pavement's bearing capacity, which can in turn be linked to future pavement performance.

The primary objective of this study was to identify data errors or anomalies in the Long-Term Pavement Performance (LTPP) load-deflection database that were not identified during routine screening required to reach level E. Routine screening applies more general procedures, such as broad range checks, to the data. The intent of this study was to review the level E deflection data and ancillary information, looking for data discrepancies and errors that routing screening may not have identified. The overall objective of the postscreening final data check was to assure that good quality load-deflection and ancillary data are available for researchers and highway engineers.

Gary L. Henderson.
Director, Office of Infrastructure
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Notice

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16. Abstract

This report presents the results of a study of pavement deflections. The study covered all level E falling weight deflectometer (FWD) deflections and associated data in LTPP's database from Data Release 9.0, November 23, 1998. Although the limited amount of data from unbound material testing was also provided, these data were not screened due to the large variations in the recorded deflections in comparison with bound layer tests.

The report covers the screening techniques developed and used to identify data errors and anomalies in the FWD load-deflection database, along with a description of each category of data errors identified. Contrary to prior expectations, the vast majority of these data errors were related to manually input data elements, not the deflections themselves. Approximately 8 percent of the 4.4 million lines, or records, in the pre-autumn 1998 load-deflection database were affected by manual input data errors alone, while less than 0.2 percent appear to be affected by actual load-deflection data anomalies generated by the FWD. Out of the approximately 8 percent of manual input data errors found, around 7 percent were associated with nonprotocol and unreported placement of the deflection sensors along the FWD's raise-lower bar. Other types of manual data entry errors, each occurring at a rate of less than 1 percent, included incorrect lane designation, station number, date- or time-stamp, test site, drop height, and configuration of the sensors for joint testing on portland cement concrete (PCC) pavements. Deflection reading data errors included deflection basin anomalies and sensor malfunctioning errors. A universally applicable deflection basin screening tool called SLIC was also developed for use on select FWD data file formats.

The overall quality of the pre-autumn 1998 FWD database can be characterized as good to excellent.

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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)

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CHAPTER 1. INTRODUCTION

BACKGROUND

The Long-Term Pavement Performance (LTPP) program, which began as part of the Strategic Highway Research Program (SHRP) and is now administered by the Federal Highway Administration (FHWA), has been gathering falling weight deflectometer (FWD) load-deflection data since late 1988. The FWD database is large—by the fall of 1998, there were already more than four million records (or lines) of load-deflection data, representing FWD tests conducted throughout the United States, Canada, and Puerto Rico. In addition, a considerable volume of ancillary information—such as sensor calibrations, pavement temperatures, sensor positions, and FWD operator observations and comments—exists as well.

The FWD database was used for comparison to screen the pre-autumn 1998 FWD level E data for errors or anomalies. The term level E refers to those data elements that have undergone a screening process already, and have been uploaded to the LTPP database for public dissemination and use. One common source of these data, and other LTPP data elements as well, is data from the various versions of DataPave.

STUDY OBJECTIVES

FWD load-deflection data are generally used to characterize the tested pavement by an analysis of the applied load and the magnitudes (or shape) of the measured deflection basin. Often, these data are used to backcalculate layered elastic stiffnesses or moduli. The results give the pavement researcher a measure of the pavement's bearing capacity, which can in turn be linked to future pavement performance.

The primary objective of this study was to identify data errors or anomalies in the LTPP load-deflection database that were not identified during routine data screening required to reach level E. Routine screening applies more general procedures, such as broad range checks, to the data. The intent of this study was to review the level E deflection data and ancillary information, looking for data discrepancies and errors that routine screening may not have identified. The overall objective of the postscreening, final data check was to assure that good quality load-deflection and ancillary data are available for researchers and highway engineers.

The majority of the errors and anomalies found during this quality assurance (QA) screening of the level E FWD database either have been, or are in the process of being, corrected. The resulting database will, in turn, be much more useful for pavement analysis and design engineers who wish to understand and properly evaluate new or rehabilitated highway pavements, based on the FWD load-deflection data in the level E database, generally using an up-to-date version of DataPave. This report documents the screening methodologies employed and the findings of this study, along with the extent of the various categories of errors and anomalies identified and reported. Specific examples of these FWD-associated data categories are also presented in this report.

SCOPE AND ORGANIZATION OF REPORT

It was initially expected that the primary thrust of this study would be a straightforward screening for anomalies in the level E load-deflection data, possibly accompanied by parallel anomalies in the peak load readings. However, it was found that the majority of the questionable FWD-associated data in the database in fact did *not* involve the deflection or load readings directly, but rather a variety of other manual data entry errors or oversights. The number and magnitude of direct equipment errors found were in fact surprisingly small, with the vast majority of the data (well over 99.5 percent) appearing to be of very good quality—highly accurate and very repeatable.

The following list is a breakdown of the various categories of errors and anomalies found, together with the approximate percentage of data affected by the questionable load-deflection data in the pre-autumn 1998 database:

- Inconsistent deflection basin anomalies: ~0.1 percent.
- Systematic load-deflection anomalies: <0.1 percent.
- Load-deflection calibration anomalies: None.
- Long-term sensor positioning errors: ~7 percent.
- Single section sensor positioning errors: 0.4 percent.
- Lane designation errors: <0.1 percent.
- Date- or time-stamp errors: 0.1 percent.
- Drop height designation errors: 0.3 percent.
- Site errors (tested at wrong test section): 0.1 percent.
- Stationing errors: 0.1 percent.

As can be seen in the list of errors and anomalies, only the first three categories are directly related to the FWD load and deflection values present in the level E database. The remaining categories have little or nothing to do with the quality of the deflection data gathered; these anomalies are generally due to inadvertent data entry errors, where manual keyboard input to the field data collection program(s) is required. Moreover, the approximate percentage of the pre-autumn 1998 data directly affected by anomalous load-deflection readings is probably less than 0.2 percent (by any reasonable measure, a very small percentage of the FWD data), while the corresponding percentage affected by other types of data errors may be greater than 8 percent. In fact, of all the error types identified, one category of error dominates all other errors combined: *Incorrectly placed sensors along the FWD's raise-lower bar over extended periods of time*. Still, the quality of the FWD data in the database has to be regarded as excellent overall. As previously noted, most of the FWD data anomalies identified by this study can be (or already have been) either corrected or flagged.

Two other categories of anomalies or potential errors were also identified in the pre-autumn 1998 FWD load-deflection data, as follows:

- Unbound layer anomalies (all data): Not screened (0.8 percent).
- Unchanged (noted only) data discrepancies: ~ 1 percent.

These two categories of data were not recommended for alteration or flagging in the database for several reasons. For the category "unbound layer anomalies," there is considerable variation in the data for most FWD test points (even drop-to-drop at the same drop height). Thus it was not possible to find any automated and reasonable criteria to sort out the "good" from the "bad" data. With respect to the general category "unchanged data discrepancies," it was deemed adequate to merely note the nature and extent of each discrepancy found; no defendable changes, deletions, or flags in the database could be justified based on available information (see also chapter 6). Since it is possible that the FWD test results (or at least many of these) are correct (or nearly so) in both categories, no changes or flags are recommended in the level E dataset for these categories of data anomalies.

The information presented in the following chapters is organized as follows. Chapter 2 describes the data obtained from the LTPP level E database, along with an overview of how these data have been organized. Load-deflection errors and anomalies are discussed in chapters 3 and 4. Categories of nondeflection associated manual data entry errors are covered in chapter 5. Chapter 6 deals with other data anomalies that have been noted but not recommended for changes or flags in the database, due to lack of definitive information. Chapter 7 presents suggested computed parameters and new FWD test procedures. A summary and conclusions are presented in chapter 8. Appendices A through M are found at the end of this report.

CHAPTER 2. LTPP DATA SCREENED AND REVIEWED

DATA REQUEST

The level E FWD load-deflection data (Data Release 9.0, November 23, 1998) were requested and received when this project began in 1998. Included with this requested information were up-to-date FWD loads and deflections, along with all pertinent ancillary FWD data. All data were then processed as described below.

DATA ORGANIZATION FOR SCREENING AND PROCESSING

The data obtained from the database were organized for detailed analyses. Specifically, the largest volume of LTPP data in the database, the FWD load-deflection data from the "∗.M06" data tables, was reorganized as follows:

1. Each level E load-deflection data record was retrieved from the database tables in comma-delimited format, with four directories (i.e., one ∗.M06 subdirectory for each of the four LTPP regions). For each regional ∗.M06 file, the data were reorganized into "sections" and "dates of test" while retaining the original format (comma delimited, columns A through W or 1 through 23).
2. For each LTPP region, subdirectories were then created using a six-character section identification name, with the first two characters being the State number and the last four being the LTPP section identification number. For example, an analysis subdirectory in Region 4 called "040122" denotes State #04 (Arizona) and LTPP section #0122 (Specific Pavement Studies (SPS)–1, section 22). In this report, an individual test section (for instance, section 040122) may also be referred to as section 04–0122.
3. For each subdirectory identifying the LTPP section, a series of "day" files then were generated. The file names correspond to the date of test at that section, using a six-digit file name in "yymmdd" format. For example, one of the files under subdirectory 040122 is 930726, which contains the load-deflection data records from Arizona's SPS section #0122, tested on July 26, 1993.
4. All subsequent data processing began with the above-outlined file format for the FWD load-deflection data. All other ancillary FWD data were left in the format in which it was received, as the size of the remaining database data files was small enough to manage on a personal computer (PC) for use in a standard spreadsheet program.

Individual FWD instruments, or machines, are identified by serial number (SN). Thus FWD SN #129 refers to the FWD with the serial number 129. In this report, serial number is sometimes referred to as unit. Thus FWD SN #129 is also identified as unit #129.

The pre-autumn 1998 comma-delimited structure of each line of load-deflection data, as recorded in the database at level E, is shown in table 1.

Table 1. Format of FWD load-deflection records from the pre-autumn 1998 database.

FWD Load-Deflection Records (Data Lines)			
	Data Structure in the Database		
Contents of Data Fields	Field	Max. # of Characters	Units
LTPP section identification number	A	4	String
State number	B	2	Integer
Construction number	C	1	Integer
Date of test	D	9	yymmdd
Time of test (24-hour clock)	E	4	String
FWD SN (FWD serial number)	F	8	String
Station number	G	6	Floating.1
Lane designation	H	2	String
Drop sequence number	I	2	Integer
Drop height	J	1	String
Peak load plate pressure (kilonewtons)	K	4	Integer
Whole history stored offline?	L	1	String
#1 deflection sensor reading (µm)	M	4	Integer
#2 deflection sensor reading (µm)	N	4	Integer
#3 deflection sensor reading (µm)	O	4	Integer
#4 deflection sensor reading (µm)	P	4	Integer
#5 deflection sensor reading (µm)	Q	4	Integer
#6 deflection sensor reading (µm)	R	4	Integer
#7 deflection sensor reading (µm)	S	4	Integer
(Not used)	T	0	Empty
(Not used)	U	0	Empty
(Not used)	V	0	Empty
Data quality level	W	1	String

CHAPTER 3. INCONSISTENT FWD DEFLECTION BASINS

INTRODUCTION TO DATA SCREENING FOR CONSISTENCY OF MEASURED DEFLECTIONS

The most basic and obvious type of FWD data error is associated with a random type of data anomaly. In this case, when one deflection, normalized to a uniform or target load level, is appreciably different from the other deflections taken at the same time and test point, a random error or a faulty deflection sensor are likely causes.

The Dynatest® Model 8000 FWD, with either the 8600 or 9000 system processor, is the only FWD device currently owned and operated by LTPP. These models advertise a deflection accuracy of ±2 percent ±2 micrometers (μm) (microns), with the 2 percent figure representing the potential systematic error (or bias) and the 2μm figure representing the random error (or precision). Since both relative and reference calibrations carried out from time to time have indicated that this claim is generally true, it was determined that using a combination of potential random and systematic error sources may be useful in finding inconsistent drop-to-drop deflection data in the database.

INCONSISTENT DEFLECTION BASIN IDENTIFICATION CRITERIA

The ±2 μm random variation associated with deflection measurements is generally stated as a one standard deviation limit, not an absolute limit. Therefore, it was immediately clear that a larger limit was necessary so as not to identify potentially good data as a random error or an inconsistent deflection basin. As an end result, the following was carried out:

1. After normalizing the deflections to the target load level, all data were marked where the deviation from the average deflection at that drop height was greater than 4μm. Usually, data from four drops at each given drop height were available. In some cases three, two, and (very infrequently) even only one drop was recorded by the equipment operator or transferred to the database through the routine (global) quality control (QC) screening processes. The initial 4-μm criterion was used in all cases except where data from only one drop were available. In those cases, the data were also marked for further screening.
2. As expected, the standard deviations associated with increasing deflections were generally larger than the standard deviations at smaller deflection levels. It was also noted that the LTPP protocol for deflection testing utilized an additional 1 percent buffer before a given drop sequence is flagged for large deviations in recorded deflections (from drop to drop at the same drop height), evidently taking into account the systematic part of the FWD's accuracy specification. Therefore, 1 percent of the recorded deflection for each sensor was then subtracted from the standard deviation as calculated above. This resulted in a considerably reduced list of suspect data records, which were called "initially flagged" data. The set of initially flagged FWD data points thus consisted of data where the standard deviation from drop to drop, less 1 percent of reading, was greater than ±4μm.
3. Each of the flagged, or marked, sets of data (whether a four-, three-, two-, or one-drop set) was then compared with the average deflection basin from a drop sequence taken at the same time and at the same test point, but from a different (unmarked) drop height. This check used both the statistical correlation (R^2) and the standard error of the estimate (SEE) between marked and unmarked data.

4. Quite expectedly, it was discovered that different types of pavement structures required different threshold levels of correlation and/or SEEs to identify truly suspect data. For example, the pavement-induced deflection variations at joints on portland cement concrete (PCC) pavements are naturally greater from drop to drop than with axisymmetrical cases of asphalt concrete (AC) or PCC interior slab data. Various types of pavement were therefore treated somewhat differently during the flagging and marking process, depending on the natural variation and deflection basin shapes of the overall data.
5. In the subsequent evaluation, it was possible to evaluate all of the data except the unbound material tests (S = subgrade and G = granular base) where the standard deviations, for all sensors and at virtually all test points, were much larger (see "Creation of LTPP Feedback Reports," below).
6. After applying appropriate R^2 and SEE limits to the suspect FWD test lines, a shortlist of inconsistent basin data records was identified and listed, by LTPP region, in a Microsoft® Excel spreadsheet. The suspect data were then subjected to further data processing, as discussed in the following paragraphs.

These marked and flagged data were an uncommon occurrence in the database. For example, figure 1 shows a typical distribution of the calculated (load-normalized) standard deviations for all AC type pavements tested along the wheelpath (designated in the database as "lane F3").

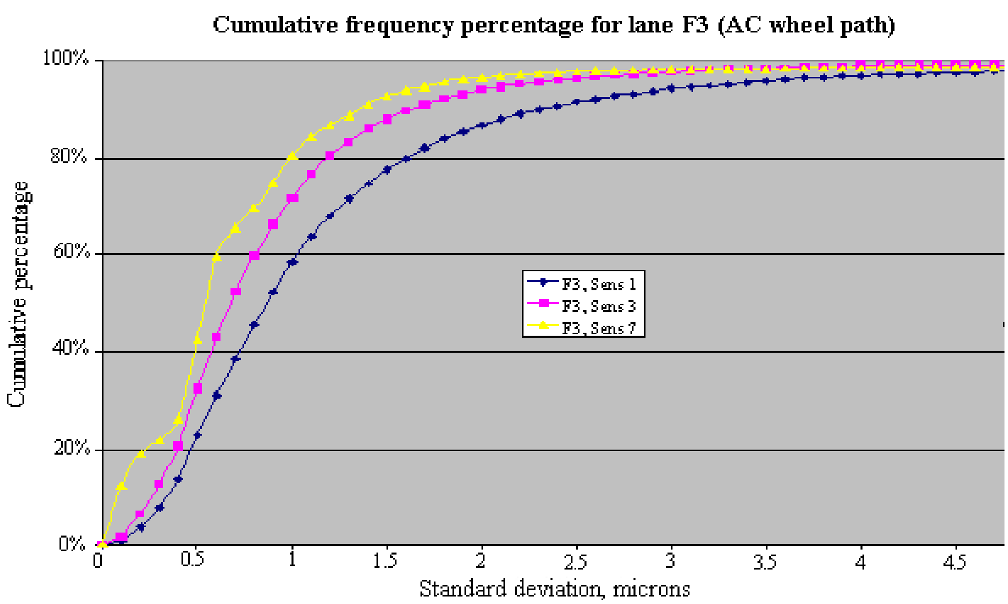


Figure 1. Graph. Frequency distribution of standard deviations for repeated deflections.

The task of identifying the distribution of standard deviations was facilitated by shifting the standard deviation limits by 1 percent of the deflection reading. As shown, a standard deviation level of 4 µm or greater (after the 1 percent of adjustment) only exists in 1 to 2 percent of the entire pre-autumn 1998 FWD load-deflection database.

After a careful review of the data, the correlation and standard deviation criteria were set for various categories or lanes of tested pavements. The data that caused the most extreme outliers were immediately flagged, while the other data were identified and marked for further assessment. These criteria are shown in table 2.

Table 2. Marked or flagged autoidentification criteria for various lanes.

Marked/Flagged	Correlation	SEE	Defl.1
Marked Autoidentification Criteria—AC surfaces (Lanes F0–F5)			
Marked	< 0.9975	N/A	N/A
Marked	From 0.9990 to 0.9995	> 18 µm	N/A
Marked	From 0.9975 to 0.9990	> 9 µm	N/A
Flagged	< 0.9900	> 9 µm	N/A
Flagged	N/A	N/A	> 2,100 µm
Marked Autoidentification Criteria—Lanes C0, C1, J1, J6, J7, and J8			
Marked	< 0.995	N/A	N/A
Marked	From 0.998 to 0.999	> 18 µm	N/A
Marked	From 0.995 to 0.998	> 9 µm	N/A
Flagged	< 0.980	> 9 µm	N/A
Flagged	N/A	N/A	> 2,100 µm
Marked Autoidentification Criteria—Lanes C2–C5, J2–J5, Ls, and Ps			
Marked	< 0.990	N/A	N/A
Marked	From 0.997 to 0.998	> 18 µm	N/A
Marked	From 0.990 to 0.997	> 9 µm	N/A
Flagged	< 0.970	> 9 µm	N/A
Flagged	N/A	N/A	> 2,100 µm

CREATION OF LTPP FEEDBACK REPORTS

The transformed basin, or SLIC method described in chapter 5 (see also appendix B) was subsequently used to reexamine the marked and flagged data selected by the automatic identification method described above. Although the method of transformed basins was developed primarily to identify sensor position errors, random errors and anomalies can also be detected from these graphs.

The SLIC technique had not been developed before the automatic identification method for inconsistent deflection basins was employed. Also, responses to our original Feedback Report (called RNS–4) of September 1999 suggested that the automatic identification method, on occasion, improperly identified suspect data, and in fact the set of drop heights used to identify anomalous data was sometimes itself a potentially anomalous set of data. Such a situation could occur, for example, when data from all four drops at a particular height were spurious but consistent with each other. These data would then pass the random error screen based on standard deviations, and then be used not only to confirm a record of anomalous data, but all the other records at that same drop height, some of which were potentially correct.

After a reexamination of all 7,045 data records originally recommended for final flagging in Feedback Report RNS–4, and with the aid of the transformed basin graphs, some of the identified data records were reclassified as good or at least okay. In addition, many of the original RNS–4 Feedback Report recommendations have by now been flagged in the current database, as so-called nondecreasing deflections (strictly speaking, these are increasing deflections, as adjacent but equal deflections are not flagged). These currently flagged data records were relabeled accordingly.

Accordingly, the new criteria only marked the most extreme anomalies or outliers. As an example, section 12–4154 tested on November 9, 1990, is shown in table 3, using the autoidentification criteria listed in table 2.

Table 3. Autoidentification example of a marked FWD data record.

Station	Lane	Hgt.	Load	D.1	D.2	D.3	D.4	D.5	D.6	D.7	Correlation	SEE	Mark?
0	F3	3	787	678	427	214	118	82	57	35	1.0000	0.54	N
0	F3	3	783	677	426	214	118	82	56	36	1.0000	0.33	N
0	F3	3	784	676	425	213	118	82	56	35	1.0000	0.28	N
0	F3	3	783	675	425	213	118	84	56	37	1.0000	0.71	N
0	F3	4	1058	817	529	282	164	113	76	48	0.9996	9.01	N
0	F3	4	1056	822	526	280	163	113	76	46	0.9997	7.92	N
0	F3	4	1057	819	525	282	160	114	74	45	0.9996	8.86	N
0	F3	4	1053	810	523	284	161	113	80	32	0.9990	13.98	Y

In this example, the criteria presented in table 2 were applied, and as a result the last line of data from the fourth drop height was marked. The average of the third drop height was used to compare the basins from the fourth drop height. As can be seen in table 3, it appears that deflection sensor #7 had too low a deflection (by about 14 µm) while #6 had too high a deflection, though by a lesser amount. Such magnitudes of deviation can have a significant impact on backcalculated moduli or other basin shape factors.

There were some cases in which none of the drop heights used at a given test point passed the 4 µm less 1 percent of reading standard deviation test, so none of the drop heights could be used for automated comparisons. In these cases, marking was accomplished visually, since in all instances at least a few of the deflection basins seemed reasonable from most or all of the four drop heights. Visual marking was an attempt to avoid flagging data that may, in fact, be acceptable and useable. An attempt was made to always have data from at least one drop left, after marking, at a given test point and drop height, although this could not be achieved 100 percent of the time.

As previously mentioned, the unbound material tests conducted directly on the subgrade or granular base layers (denoted by an S = subgrade or a G = granular in the lane designation) were too variable to separate real errors or anomalies from the actual pavement response. There were several causes for this problem; those causes are described in the following paragraphs.

The FWD equipment provided to SHRP and the LTPP program was not specifically designed to test unbound materials, although with careful handling it can be used successfully for unbound material tests. The load plate on the LTPP program's FWD equipment is not segmented or split.

When unbound materials are tested, the mean pressure under the loading plate should be reduced to a level similar to what that particular layer will experience, under traffic, after the bound layers are in place. In most cases when unbound materials were tested, not only was the small 300-millimeter (mm) (117-inch) loading plate used in lieu of the provided 450-mm (136.5-inch) loading plate, but the ordinary weight package and standard drop heights used for bound material tests were occasionally employed as well. This often resulted in deflections that were too large, sometimes even exceeding the physical limits of the FWD's ~2,100 µm sensor range. Further, this problem not only occurred on a regular basis for the center deflection, but for sensors 2 and 3 from time to time, especially in the case of subgrade tests. Use of the 450-mm (136.5-inch) plate results in better confinement of the materials under test, which is more realistic.

All of these factors contributed to several spurious deflection readings observed throughout the S- and G-tests conducted for the LTPP program and later uploaded as level E data into the database. In addition, unbound materials often behave nonelastically, with plastic deformations, punching, and shear deformations taking place simultaneously on a fairly regular basis.

Nevertheless, no flags or other changes to the data are recommended to the S- and G-data, because *some* of the deflection readings—particularly those between d2 and d5—often appear to be reasonable. These data alone may prove to be valuable for analysis of unbound material tests, since backcalculation is not likely to be used to derive stiffness data for one, or at the most two, layer(s) in the pavement structure.

Except for the unbound material test data, the automated and manual (visual) processes described in the foregoing paragraphs were applied to all of the pre-autumn 1998 load-deflection data from all four regions. A list of recommended flags was developed, and a revision of Feedback Report RNS–4 was created, called RNS–4M (shown in appendix A). Table 4 shows the number of recommended flagged records versus the approximate number of records in the corresponding pre-autumn 1998 "∗.M06" files in the LTPP database.

Table 4. FWD records identified for flagging in the pre-autumn 1998 database.

All LTTP Data	Total Number of Records (lines)	Total Number of Recommended Flags	Percentage of Recommended Flags
TOTALS	4,422,000	2,642	0.06

As shown in table 4, on a percentage basis the overall number of recommended flags is very small. The errors identified were possibly attributable to equipment operators not noticing when something was wrong with a particular sensor or sensors. Much of the flagged data was sequential (i.e., from the same day and along the same test section). It is also possible that there were intermittent problems with the equipment that could not be immediately rectified in the field.

Finally, it should be noted that other flags were originally recommended in Feedback Report RNS–4; however, most of these were corrected or changed through other screening methods, such as the visual SLIC method (see chapter 5) or the use of the nondecreasing deflections flag mentioned above. With respect to the use of flags in the load-deflection tables, such as those recommended in Feedback Report RNS–4M (see appendix A), a Feedback Report designated RNS–7 was submitted. This feedback report is also presented in appendix A.

CHAPTER 4. OTHER LOAD-DEFLECTION DATA ERRORS

DATA SCREENING

In the process of performing additional data screening procedures, a number of other categories of data errors or anomalies associated with specific (individual) records in the load-deflection database were discovered. These were subdivided into three categories, as follows:

- Systematic load-deflection errors.
- Section identification errors (tested at wrong test section).
- Double data (time stamp) errors.

SYSTEMATIC SENSOR ERRORS

Only one complete systematic error example was found: in one day file, the center (#1) sensor consistently read between 0 and 4 µm, while the deflection levels for neighboring sensor #2 were in the several hundred micrometers range. This was section 83–1801, tested on May 13, 1994. This data error was reported in a September 1999 Feedback Report designated RNS–5 (see appendix A). Evidently, the erroneous section 83–1801 data have been removed from the level E load-deflection database. There were also other relatively infrequent occurrences of systematic and incorrect sensor #1 readings. Feedback Report RNS–5 recommended that all erroneous data records be culled from the level E database. To date, some of these records appear to have been corrected while others have not.

The one day file, already culled, plus the handful of minor examples correspond to about 0.015 percent of the total volume of FWD data in the entire pre-autumn 1998 database.

TEST SECTION ID ERRORS

Five section errors were also found, where the FWD operator evidently tested the wrong test section. These particular day files did not bear much, if any, resemblance to the other dates of test, reportedly along the same test section and at the same test points. In fact, there were several other instances in which it was unclear whether the correct test sections were recorded. Only those cases where it is virtually certain that the wrong section was visited were recommended for culling in Feedback Report RNS–5 shown in appendix A. In total, these anomalies correspond to less than 0.1 percent of the total volume of pre-autumn 1998 data in the database.

A sample section error is shown in figure 2, where the deflections of sensor #5 (mainly corresponding to the response of the subgrade) are plotted as a function of station number and date of test. The tests conducted on August 1, 1996, bear little resemblance to the tests conducted on that section on any previous dates, even those as recent as 6 months earlier. This erroneous dataset was deleted from the database, as recommended.

After Feedback Report RNS–5 was submitted in September 1998, two of these five section error datasets were evidently deleted from the database, as recommended. The other three were not deleted due to a differing opinion from the appropriate Regional Coordinating Office (RCO).

After careful re-examination, we still recommend deleting two of the remaining three day file data record sets, due to the overwhelming evidence that the incorrect sections were in fact tested as previously reported. These record sets are from the test sections incorrectly identified as 04–0213 tested on March 6, 1995, and 08–0216 tested on August 5, 1998.

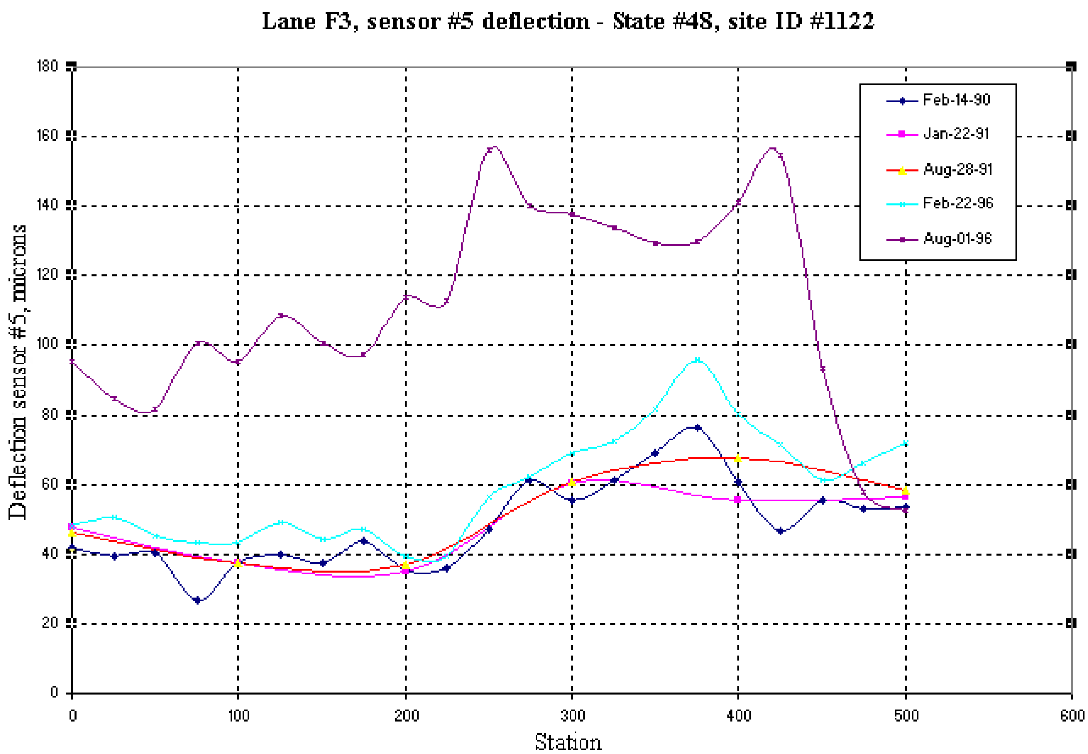


Figure 2. Graph. Sensor 5 deflection readings for one LTPP section.

The third unresolved section (identified as section 08–0213) has by now been tested four times, with the last test occurring well after Feedback Report RNS–5 was originally submitted in 1998. The data now appear to be grouped into two pairs: two of the four datasets appear to be from the same section, as does the other pair. But all four datasets, in all likelihood, are *not* from the same test section. We recommend that these four datasets be further investigated, to determine which pair is correct and which pair is (most likely) incorrect. If the RCO can verify that all four deflection sets are actually from the same test section, it would be very important to study this section in more detail, since the changes in deflection would mean that the stiffnesses of the pavement materials have changed more than considered possible based on our current knowledge of pavement materials and their potential changes over time. If such changes really did occur, either in the material properties or pavement system properties, it is essential that the pavement community understand what and why this occurred. In this possible (but unlikely) event, the mechanistic design methods currently under development should be able to account for such behavior.

DOUBLE DATA AND INCORRECT TIME STAMP ERRORS

In many instances, double data were found in a series of day files, generally with a 1-hour difference (exactly) in the time stamps, all other data items being identical. Other examples of double data included incorrect lanes and incorrect station numbers, although these were relatively infrequent occurrences. In the majority of these cases, evidently the FWD operator had his/her computer set for the wrong time zone, missed a daylight savings shift, or entered the wrong set of lanes or station numbers. These discrepancies were most likely discovered later, probably during the execution of routine QA procedures at the regional offices. Presumably, someone in the office then edited the data by changing the time input by 1 hour (for example, to correspond to the pavement temperature measurements made at the same section and times), and then refiltered the deflection data into the regional database. In the process, however, the (incorrect) data lines were inadvertently left in the database, and all of these data were eventually transferred as level E data to the LTPP database. Therefore, all lines of double data (i.e., the lines with incorrect time stamps, lanes, or stations) were recommended for culling in Feedback Report RNS–5 (shown in appendix A).

Double data records only corresponded to approximately 0.03 percent of the total volume of the pre-autumn 1998 data in the database. However, at this time only some of these records have been corrected. It has been re-recommended that the remaining double data records in the load-deflection database be culled. Most of these records are in one of the four regions that have not yet responded to Feedback Report RNS–5.

CHAPTER 5. DATA ENTRY ERRORS

DATA SCREENING

In the course of screening for load-deflection errors, several types of generally correctable data entry errors were identified. These include the following:

- Long-term sensor positioning errors.
- Single section sensor positioning errors.
- Lane designation errors.
- Recorded date errors.
- Drop height designation errors.
- Other minor data errors.

LONG-TERM SENSOR POSITIONING ERRORS

Probably the most important—and by far the most common—form of data entry errors found in the FWD-associated database occurred during a simple, incorrect (and obviously inadvertent) *manual recording* of the actual sensor positions along the FWD's raise-lower bar. In virtually all instances where this occurred, the FWD deflection sensors appeared to be functioning normally, and the only anomaly was an oversight rather than a fatal equipment malfunction or irreparable error.

After a long search for a satisfactory method of screening for such errors, a method was devised whereby the deflection basin was transformed into nearly a straight line through a process called the SLIC transformation or transformed basin method. SLIC (pronounced "slick") is an acronym for the authors of a 2000 paper—Stubstad, Lukanen, Irwin, and Clevenson.[1] Background and early development information on the transformed basin procedure are covered in this paper, which was prepared for the Transportation Research Board (TRB) and is largely based on the LTPP data-screening project reported in this report. A copy of this draft paper is included in the 2000 TRB preprint compact disk (CD), and the paper was subsequently published by TRB.

An automated version of the SLIC procedure was eventually developed to screen the FWD database more thoroughly, whereas a visual-manual method was used when the sensor positioning errors were first identified with certainty in 1999. The technical details of the screening method are described in appendix B.

The automated screening method uses a slightly different transformation of the deflection versus offset data than the visual method. Instead of a plot of ln-ln normalized deflection versus ln offset (as the visual method employs), the automated method predicts the position of sensors using two variable exponents (depending on sensor position) and a regression equation. This process has removed the previously identified bias from the method (particularly for the prediction of sensor d7 on the seven-sensor LTPP basin configuration), so that, on average, sensor position predictions will be equal to the protocol position in the LTPP database in cases where the sensor positions were *not* suspected to be in error. Using the automated SLIC method, the precision of the prediction model also improved appreciably.

The visual method transforms a normal S-shaped deflection basin into a straight or smoothly curved line, assuming the measured deflections and the offset distances to the sensor holders are all correct.

Table 5 presents the identified sensor positioning errors for each FWD used by the LTPP program, along with an associated period of time. Only the errors that are *certain* (i.e., those that can be verified through both the manual/visual *and* automated sensor prediction processes, together with other means and sources of evidence) are recommended for change in the database. In some cases, less serious sensor positioning errors may also exist; however, since these are not as certain, they were not flagged or recommended for change in the database.

Table 5. FWD unit- and time-specific sensor positioning errors in the database.

Region and FWD SN	Dates Affected (inclusive)	Actual Sensor Positions (in appropriate units)	# of Test Dates
Reg.1–SN129 [1]	November 3, 1995 to April 14, 1996	0, 8, 12, 18, 24, 36 and 48 inches	≡ 21
Reg.1–SN129 [2]	April 15, 1997 to May 21, 1997	0, 8, 12, 18, 24, 36 and 48 inches	≥ 12
Reg.1–SN058 [3]	October 15, 1997 to March 5, 1998	0, 9, 12, 18, 24, 36 and 60 inches	≥ 22
Reg.2–SN061*[4]	August 4, 1989 to August 10, 1989	0, 200, 300, 600, 750, 1200 and 1800 mm or: 0, 8, 12, 24, 30.5, 48 and 72 inches	≥ 4
Reg.2–SN130 [5]	August 25, 1994 to September 7, 1994	0, 8, 12, 18, 36, 48 and 60 inches	≥ 16
Reg.3–SN075 [6]	January 17, 1990 to January 22, 1990	0, 8, 12, 18, 30, 42 and 66 inches	≥ 4
Reg.3–SN132 [7]	July 29, 1996 to October 25, 1996	0, 8, 12, 18, 24, 36 and 48 inches	≥ 29
Reg.4–SN061*[4]	<February 26, 1989 to September 8, 1989	0, 200, 300, 600, 750, 1200 and 1800 mm or: 0, 8, 12, 24, 30.5, 48 and 72 inches	≥ 97
Reg.4–SN061 [8]	July 17, 1995 to October 31, 1995	0, 8, 12, 18, 24, 36 and 48 inches	≥ 65
Reg.4–SN131 [9]	<May 24, 1994 to April 30, 1996	0, 8, 12, 18, 24, 36 and 48 inches	≥ 191
Reg.4–SN131[10]	December 15, 1997 to January 20, 1998	0, 8, 18, 24, 36, 48 and 60 (or 66) inches	≥ 8

1 inch = 25.4 mm

* Same FWD, same period of time—LTPP field tests conducted in two different regions.

Table 5 notes based on SLIC analyses, plus a variety of information sources:

1 *Information obtained from Region 1 has revealed that the correct position for d7 should have been 121.9 cm (48 inches), due to the presence of a (usually unoccupied) sensor holder at this position at the time. A closer look at the data, using some of the clues and information provided by Region 1, verified that the actual position of d7 was121.9 cm (48 inches), as previously reported in April 1999. Region 1 also reported that there were 21 affected day files, not 19 as originally identified. Further, Region 1 has determined that a relative calibration took place on November 2, 1995, which is probably the date when the seventh sensor was*

inadvertently placed into the wrong sensor holder. No LTPP tests with number (SN) 129 were performed between December 15, 1995, and April 30, 1996. On April 15, 1996, a calibration was performed on SN 129 (after annual maintenance at the Dynatest facility in Florida), which is probably the date the d7 sensor was repositioned correctly. Subsequently, this result has been verified through the automated SLIC process and other cross-checks (see appendix C).

2 *This relatively short-lived sensor positioning error for sensor 7 on SN 129 was revealed during the automated SLIC process rescreening of the 1999 reported sensor positioning errors. This error appears to be identical to most of the other reported errors; sensor 7 was inadvertently placed in the (usually) unoccupied sensor holder at position 121.9 cm (48 inches). This result has been verified through the automated SLIC process and other cross-checks (see appendix D*).

3 *Although very few LTPP tests were conducted during the affected 1997–98 winter time period, this relatively long-term senor positioning error was identified by the automated SLIC process used to rescreen the previously reported sensor positioning errors. This SN 058 error was unique in that it appears that the sensor 2 holder accidentally slid forward (away from the loading plate) approximately 25.4 mm (1 inch), to a position some 22.9 cm (9 inches) from the center of the loading plate, instead of the normal 20.3 cm (8 inches) protocol position. This result has been verified through the automated SLIC process and other cross-checks (see appendix E*).

4 *Information obtained from Region 4 has revealed some important clues that reflect the metric sensor positions reported in table 5. Tests were conducted using SN 037 (Nevada Department of Transportation's (DOT) FWD) side-by-side with SN 061, with reported SN 037 positions of 0 mm, 200 mm, 300 mm, 600 mm, 850 mm, 1400 mm, and 1800 mm (0 inch, 7.87 inches, 11.8 inches, 23.6 inches, 33.6 inches, 55.1 inches, and 70.9 inches) on September 14, 1988. It appears that the operator of SN 061 may have attempted to configure the SHRP FWD using these metric sensor positions. Alternatively, it may have been delivered from Dynatest with this set of default positions. However, two of the seven sensors were placed in positions different from those of the Nevada DOT's unit, although possibly still in metric positions. Further, these incorrect sensor positions were maintained through September 8, 1988, inclusive, after which the sensors were evidently repositioned to their correct protocol positions. Alternatively, the automated SLIC analyses and other cross-checks employed indicate that the sensors may have been placed in the following positions: 0, 0, 8 inches, 12 inches, 24 inches, 30.5 inches, 48 inches, 72 inches (see appendix F*). *These positions are, for all practical purposes, identical to the metric positions reported previously (the overall SLIC curve fit is slightly better using the U.S. standard positions shown in table 5).*

5 *Information obtained from the former regional coordinator in Region 2 has revealed that there was, in fact, an extra sensor holder placed at 121.9 cm (48 inches). This position should have been empty, but in this case it was inadvertently occupied by sensor 6. Meanwhile, sensor 5 was inadvertently placed in the 91.4-cm (36-inch) sensor holder. Based on this information and the SLIC analyses results, it is certain that the actual empty sensor holder during this suspect period of time was at the 61-cm (24-inch) position instead of the 121.9-cm (48-inch) position, which would precisely explain the sensor position discrepancies reported. Subsequently, these results have been verified through the automated SLIC process and other cross-checks (see appendix G and also figure 4*).

6 *Discussions with Region 3 personnel have revealed that the field crews involved at the time do not believe there were any errors in sensor position. Extensive backcalculation conducted on deflection data, where both suspect and nonsuspect data are present, indicate that the sensors during this first Puerto Rican project were placed by measuring the distances from each successive sensor to the following one, instead of by measuring the distance from the center sensor to each of the others individually. Thus only one error in sensor spacing measurements was made, which was evidently between sensors 4 and 5 and which, in turn, were*

inadvertently placed 30.5 cm (12 inches) apart, instead of the protocol 15.2 cm (6 inches) apart. Then, sensors 6 and 7 were both placed the correct distance from sensor 5. As a result, each of these three outer sensors was also inadvertently placed 15.2 cm (6 inches) too far from the loading plate. The backcalculation evidence was overwhelming in terms of RMS error and probable (i.e., reasonable) modulus values. Subsequently, these results have been further verified through the automated SLIC process and other cross-checks (see appendix H).

7 *Discussions with Region 3 personnel have revealed that the field crews involved at the time do not believe there were any errors in sensor position. However, the regional coordinator believes that the reported error in the position of sensor #7 very possibly existed, although this was obviously unknown to the field crew at the time. Extensive backcalculations on LTPP sections with both suspect and nonsuspect data have revealed that this sensor positioning error did, in fact, occur during the reported time period, with overwhelming evidence in terms of RMS error and reasonableness of backcalculated modulus values. These values were also compared with backcalculated values from other dates of test at the same test sections. As a result, it is evident that there was a spare sensor holder (which should have been empty) placed at the 121.9-cm (48-inch) position, just as occurred in many of the other anomalous datasets in other LTPP regions. Subsequently, this result has been verified through the automated SLIC process and other cross-checks (see appendix I).*

8 *An investigation of calibration dates, possible errors in terms of spare sensor holders, and field notes has revealed that the actual sensor positions were precisely as listed in table 5. Please note that the error evidently made in the d7 sensor position is the same error as was found in numerous other cases in three out of four regions. Sensor 7 was simply placed in the 121.9-cm (48-inch) holder (which should have been unoccupied). This conclusion has also been verified through the automated SLIC process and other cross-checks (see appendix J).*

9 *A thorough investigation—using delivery and/or calibration dates, possible errors in terms of spare sensor holders, and field notes—has revealed that the sensor positions listed in table 5 are definitely correct. Furthermore, in this particular case, there was also an actual physical measurement of sensor positions made when this error was previously discovered in connection with another LTPP study in 1996. Please note that the error made in sensor position is the same error that has occurred in numerous other cases, wherein sensor 7 was simply placed in the normally unoccupied 121.9-cm (48-inch) sensor holder. Backcalculation was also used to verify the actual sensor positions, including verification of the exact dates when the reported error began and ended. Finally, this result was also verified through the automated SLIC process and other cross-checks (see appendix K).*

10 *Information obtained from Region 4 has confirmed that the sensor positions listed in table 5 are correct. SN 131 was used for testing at WesTrack on January 29, 1998, where the sensor positions should have been as listed, except that sensor 2 should have been placed at 30.5 cm (12 inches) instead of the 20.3-cm (8-inch) LTPP protocol position. Some backcalculation was performed on the data that also confirmed the reported sensor positions. Subsequently, these results have been further verified through the automated SLIC process and other cross checks, although the result of the automated SLIC analyses indicate that sensor 7 was at approximately 167.6 cm (66 inches) instead of the 152.4 cm (60 inches) previously reported (see appendix L). Whether sensor 7 was in fact positioned at the protocol 152.4-cm (60-inch) position, or at the calculated ~167.6-cm (66-inch) position, cannot be determined with certainty.*

Table 5 reflects the sensor positions that were used during each given period of time and with the specified FWD unit, as listed in the table. When concrete joints were tested, the protocol called for the FWD operator to move sensor #2 to a position 30.5 cm (12 inches) behind the loading plate.

This was usually—but not always—carried out; however, this error category is dealt with elsewhere in this report.

It is very important to review all the graphs shown in the referenced appendices for each example shown in table 5 and its footnotes. In each case, it can be argued "a picture speaks a thousand words." Further—in each case—there can be no doubt whatsoever that the sensor positioning errors listed in table 5 are correct and highly accurate.

As can readily be seen in table 5, long-term sensor positioning errors occurred infrequently but in all four regions, in many cases over relatively long periods of time. Such errors also occur, with unknown frequency, elsewhere—whether with State and other DOTs, National Road Administrations, or private consultants. The authors of this report have identified numerous instances where other FWD-sourced data was found to be incorrect due to sensor position reporting errors by equipment operators. In most of these cases, these errors were identified much earlier in the process, generally within a week or two of each occurrence. For the LTPP program, the good news is that changing the database sensor configuration tables to reflect the actual (as opposed to protocol) sensor positions, when such data entry errors generally occurred with an astronomically high probability, can easily rectify these inadvertent but very important errors.

To further illustrate how the visual SLIC method works, examples of four transformed deflection basins are shown in figures 3 and 4. The deflection basins are from two sections tested 1 year apart. The data are the SLIC data from FWD SN 130 in line 5 of table 1, and footnote 5 to which this line refers.

First we assume that the sensor positions were as reported in the database (in this case, the protocol positions) in all four of the illustrated cases. Based on the visual data in figure 3, it can clearly be seen that sensors 5 and 6 were misplaced along the raise-lower bar during the 1994 tests, while they were properly positioned during the 1995 FWD tests performed at the same LTPP sections about one year later. Under normal circumstances, each pair of lines should very nearly parallel one another.

In figure 4, the two basins where sensors 5 and 6 were misplaced by 30.5 cm (12 inches) are replotted using their actual positions against the two correct (protocol) basins. Here it can be seen that the two pairs of lines are almost perfectly parallel; in fact, for all practical purposes, they overlap.

It is of vital importance that the positions of the FWD's deflection sensors are known quite precisely. It has been shown in numerous studies, including the TRB paper referred to earlier, that even very small errors in deflection reading accuracy affect the results of backcalculation appreciably.[(1)] It is not difficult to imagine, therefore, that if a given deflection sensor is even a small percentage of its plate distance away from its reported position, the results of backcalculation will be markedly affected.

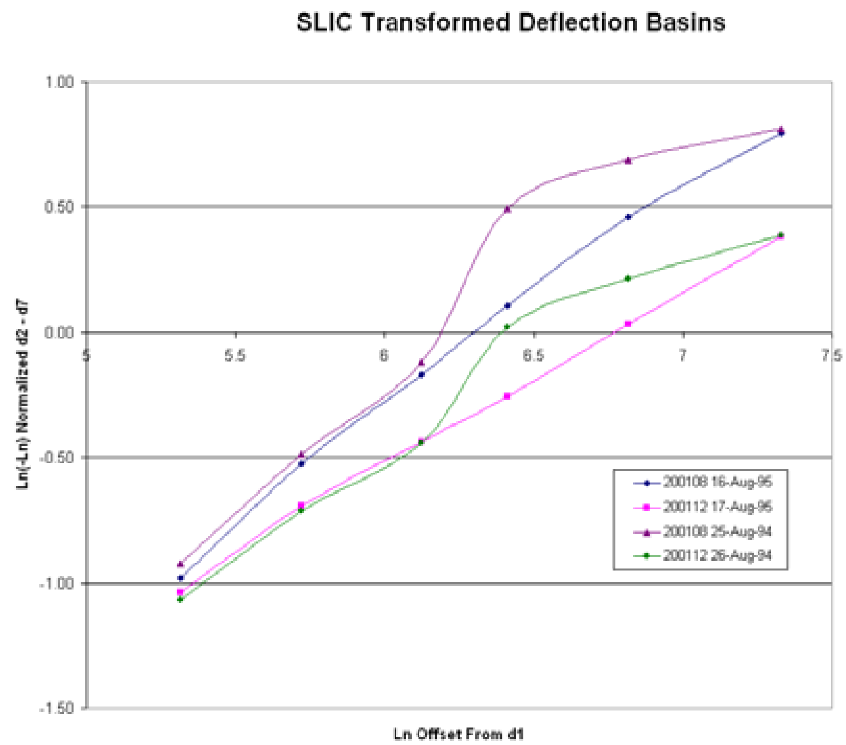


Figure 3. Graph. Sample deflection basins transformed with SLIC (input protocol positions).

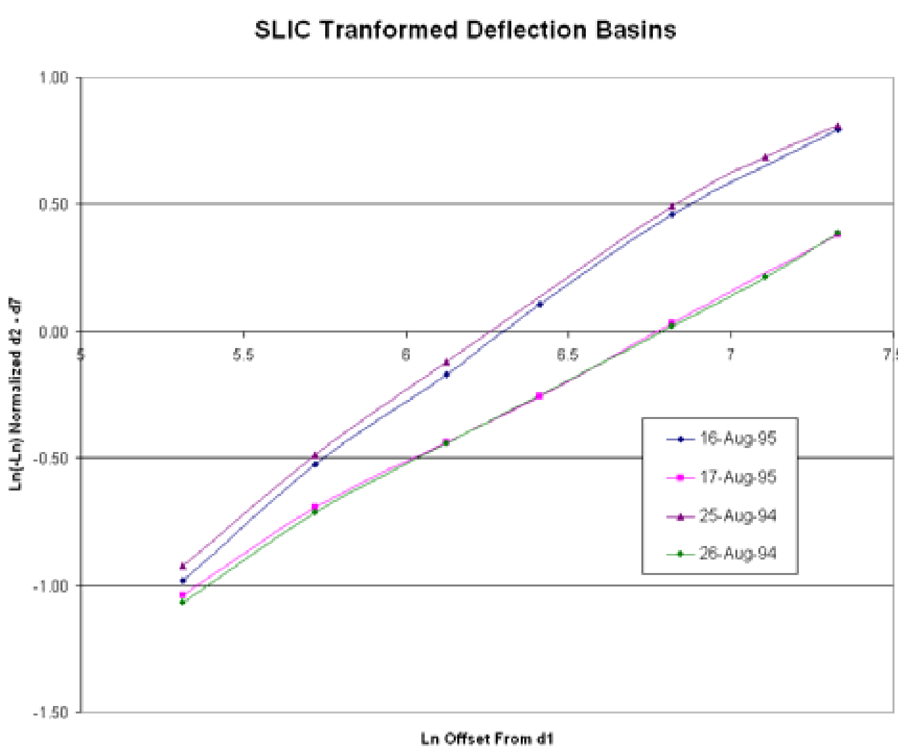


Figure 4. Graph. Sample deflection basins transformed with SLIC (input actual positions).

The LTPP program has gone to great lengths to ensure, through periodic relative and reference calibration procedures, that the FWD's sensors are reading correctly, even to a better accuracy than advertised by the manufacturer (±2 percent ±2 μm). Since inadvertent and therefore unreported shifts in sensor position, such as those listed in table 5, generally change the measured deflections by *at least* 10 μm (usually more), this effect will be profound—unless the particular sensor or sensors in question are ignored in the backcalculation process.

Statistical Calculations Supporting the Recommended Changes to Sensor Positions

There are several standard ways to support the changes being recommended. In the referenced TRB paper, there is a two-sample T-test that can be used to determine whether the data from the dates in question, produced by the FWD on the dates in question, comes from the same population as the population of data produced by this same FWD on dates outside of the suspected interval.[1] The data in both cases are the predicted values of the sensor positions for the hypothesized erroneous sensor position. The P-value for this test is smaller than 10^{-52}, a value so small that to continue to accept that hypothesis would be foolish. In plain language, if the sensor had not been moved during the suspect period, the probability of data so different for this period as that actually observed is nil; these data could not have happened.

These calculations leave open the question of which hypothesis should replace the hypothesis that clearly requires rejection, that is, the hypothesis that the sensor remained at 152.4 cm (60 inches) throughout the time period identified. Several points need emphasis. One is that the automated method used to predict sensor positions was the same regardless of which of the above-described errors was identified. One of the suspected errors, shown in the next-to-last row in table 5 with 191 or more dates in error, was confirmed independently by other means. At that time, it was confirmed through a physical measurement that the d7 sensor was offset 121.9 cm (48 inches). Furthermore, there was a sensor holder in the raise-lower bar at 121.9 cm (48 inches). A position of 121.9 cm (48 inches) is therefore natural to hypothesize, and to compare with the hypothesis that the sensor is at 152.4 cm (60 inches).

One standard method of comparison is the likelihood ratio. The technical details of the likelihood ratio computations are shown in appendix M. The likelihood ratio compares the ratio of the probabilities of data under competing hypotheses. If H48 is the hypothesis that sensor 7 was offset 121.9 cm (48 inches), and H60 is the hypothesis that sensor 7 was offset 152.4 cm (60 inches), then the likelihood ratio computes P48 (data given that H48 is true) divided by P60 (data given that H60 is true).

Since the sensor error for FWD data with SN 8002–131 from May 1994 to April 1996 is not questionable, the likelihood ratio was computed for other sets of data. This was done for three other sample sets of data from table 5: one set with a small number of dates, one with a moderate number of dates, and one with a large number of dates, but different from the confirmed case containing 191 dates.

An abbreviated summary of the likelihood ratio calculations appears in table 6.

Table 6. Likelihood ratios for protocol versus nonprotocol sensor positions for d7.

Serial Number	Start Date	End Date	Number of Dates	Mean d7 Prediction (inches)	Likelihood Ratio	Standard Deviation (inches)	95% Confidence Interval (inches)
8002–129	4/15/97	5/21/97	12	47.99	2,260	1.96	(46.7, 49.2)
8002–132	7/29/96	10/25/96	29	48.12	5,773,093	2.36	(47.2, 49.0)
8002–061	7/17/95	10/31/95	65	47.20	33,706,837,035	1.39	(46.9, 47.6)

1 inch = 2.54 cm

In short, in the *least* compelling case, the data are over 2,000 times more likely to have occurred with the sensor 7 at 121.9 cm (48 inches) than with this sensor at 152.4 cm (60 inches). It should be re-emphasized that great effort was made to find an automatic prediction method that was apparently unbiased for predicting sensor 7, when sensor 7 was correctly positioned at 60 inches, and with good precision.

Corroborating evidence confirms that the predictions of the position of sensor 7, with the same FWDs before and after the period in question, do not suggest any anomalies. Additionally, tests conducted during the period of time in question, on the same test sections but with different FWDs, also do not produce unusual (nonprotocol) sensor 7 predictions. Finally, in most cases there is additional evidence that the starting and ending dates are correct. For example, there generally was a calibration of the particular FWD in question between the ending date in table 5 and the first date the same FWD was used after calibration, when the sensor(s) were repositioned to their protocol positions. However, only the outputs of the predictions of the sensor(s) in question were used to construct table 5 (see the footnotes and appendices to table 5 for many other examples). All this evidence was further corroborated by extensive backcalculation in most of the table 5-listed cases of nonprotocol FWD sensor positions in the database.

RNS–2 AND RNS–2M FEEDBACK REPORTS

The occurrence of long-term sensor positioning errors was first reported in September 1999 (Feedback Report RNS–2). After that report was submitted, it was not universally believed that there could have been such errors made in sensor positions, at least to the extent indicated by RNS–2.

Subsequently, a trial of the SLIC method was conducted, wherein it was quite clearly shown that one can, in fact, predict actual sensor positions (or sensor errors) using the SLIC method as long as some supporting information is included, such as the type of data included in the extensive LTPP database and shown in appendices C through L. Subsequently, the semiautomated method was developed to rescreen the entire pre-autumn 1998 database, to verify or reject the findings thereof.

The result was an even more certain verification—almost to the letter—of the previous findings. In addition, two other previously undetected (though relatively short-term) sensor position errors were detected. The original eight occurrences (corresponding to nine of the lines in table 5, two of which are overlapping) and the two newly identified errors are all described in this chapter under the heading “Long-Term Sensor Positioning Errors.” Further, these findings are now supplemented by a variety of supporting information and graphs presented in the appendices.

As a result of these findings, Feedback Report RNS–2M was submitted. This Feedback Report is also shown in appendix A. RNS–2M was accompanied by most of the associated information presented in this report, together with a copy of table 5 as presented here.

The LTPP database user should use extreme caution when any load-deflection data from these ten periods of time, and the same FWD serial number, are used for analyses. Although presently the LTPP database still reports protocol sensor positions, these data are not correct; use of these data will result in incorrect analyses unless the sensor(s) in question are ignored when analyzing the FWD data.

DEVELOPMENT OF A SCREENING PRODUCT USING THE TRANSFORMED BASIN METHOD

Based on the SLIC-based screening of the LTPP database, as discussed previously, a SLIC product was developed for use in the field. This product can conduct an automated SLIC screening of FWD data directly on the FWD's output, as long as the data file has been closed and stored. Presently, this product is limited to Dynatest FWD field program generated load-deflection data, gathered and stored in Edition 25 output format.

The original SLIC screening procedure tended to underestimate the position of the last sensor, sensor 7, in the LTPP database. Also, the semiautomatic version of that procedure described in the literature produced estimates that had an undesirable amount of variability.(1) Many models for the data were tried, and eventually a model that would estimate the position of the outer sensors without bias was found. A similar attempt was made to improve the estimate of the position of the inner sensors. This effort was also successful, but unfortunately a slightly different model was the most accurate, with (virtually) zero bias and good precision.

These semiautomatic models are most useful for trying to correct errors in recording the position of the LTPP sensors. In these situations, the visual or automatic SLIC procedure has identified a period of time when the position of a particular sensor was apparently not properly recorded, and one must estimate the actual sensor position without being able to directly examine the FWD unit itself. Accordingly, the field product should have a different function, since the FWD operator has the opportunity to measure the sensor positions and/or check the sensors for other errors, and correct any sensor positioning error on the spot if necessary. Further, the operator can adjust the already recorded data to reflect the actual sensor positions of those measurements already made in cases when a sensor is positioned incorrectly. Accordingly, the most important function of the SLIC field product is to alert the operator that there is, or may be, an error in the positioning of one or more sensors, and for the operator to check them.

The newer models and the older semiautomatic models were compared on large sets of data from LTPP where there was a high degree of certainty that the sensor positions were correct, and also where it was apparent that a sensor positioning recording error had been made. Various criteria were employed to detect that a sensor positioning error existed. As one might guess, no procedure is flawless, and the two kinds of errors inevitably compete with one another. One type of error is a false alert. This error occurs when the data meet the criterion for detection of a sensor positioning error, but in fact the sensors are positioned correctly. The other type of error is failure to detect. This type of error occurs when the screen for a sensor positioning error fails to be triggered by data that are measured with a sensor positioning error, or errors.

The second type of error should be regarded as more serious, since this error produces data that may result in false information. The first type of error is an inconvenience to the operator, and may require the operator to do an unnecessary measurement that confirms the FWD sensors are correctly positioned and correctly functioning. To minimize the occurrence of failure-to-detect errors, the most reliable procedures were based on the R^2 values from the original SLIC procedure, that is, the procedure used in the visual graphics approach (see, for example, figures 3 and 4). This procedure fits a quadratic function to y = ln (-ln(normalized deflection)) versus x = ln(offset), and then computes the value of R^2. (Normalized deflection in this case is not load-normalized, but rather deflection-normalized, meaning that each offset deflection is divided by the center sensor deflection, resulting in a normalized deflection basin with a maximum center sensor deflection of 1.0.) R^2 measures the ratio of squared deviations of predicted values (of y) from the mean of y to the squared deviations of actual data from the mean of y. The LTPP data usually produce R^2 values (for the transformed basins) that are remarkably close to 1, frequently above 0.998. However, there are occasional values not so close to 1 from FWDs with correctly recorded sensor positions. Values less than 0.990 suggest that there may be a sensor positioning error, and values less than 0.980 are strong evidence that a sensor positioning error exists.

In view of these facts, the SLIC field product is designed to alert the operator that there may be a sensor positioning error whenever the value of R^2 falls below 0.990, and that there is strong evidence of an error whenever this value falls below 0.980. The graph of the data can be seen by the operator and, with practice and familiarity, this person will learn to see the graph as an indication of which sensor may be out of position.

The SLIC transform produces a graph with a nearly straight, somewhat concave, downward smooth line, with no kinks (changes in concavity). If the operator can measure the actual FWD sensor positions and find an error, the values of the sensor positions can be changed on the spot (in the field data file) and the change can be viewed in the plotted SLIC transformed data. On the other hand, if the sensors are in their correct positions, an operator may have found a false alert error unless there is a physical problem with a given sensor or sensor holder, for example. In this case, the operator should record that finding in the field file so that the person doing the analysis will be aware that the data has an anomaly, and that the sensor positions were checked and confirmed. If the situation continues to persist on several sections, a relative calibration should be done to confirm that the suspect sensor is functioning correctly. False alerts will presumably happen more often than the failure-to-detect errors, which will necessarily go uncorrected.

Note that, the more often an operator runs the SLIC sensor position check, the greater the likelihood that a false alert will occur, but the less likely it is that the more serious failure-to-detect errors will occur. Larger sets of data tend to produce fewer errors of either type. Nevertheless, the operator should be encouraged to perform a SLIC check at the end of each section tested or day of testing, before moving off a site or before opening a new data file. Please note that files that contain concrete joint data, where the joints are positioned between two of the sensors, should *not* be run through the SLIC field product, since this kind of data will almost always result in a false alert error due to the influence of the joint on the measured deflections. False alerts are also likely on badly distressed pavements, or on pavements where bedrock or loose gravel is close to the surface.

SINGLE SECTION SENSOR POSITIONING ERRORS

As opposed to the type of long-term sensor positioning errors described above, there were several instances of day files where sensor number 2 (d2) was placed different from that recorded by the FWD operator. These cases almost always involved joint testing on PCC pavements (i.e., J4 and J5 or C4 and C5 tests), or tests conducted along the same line as these joint tests (e.g., J6).

Three categories of short-term sensor position designation errors were identified and recommended for correction in the database:

- d2 was recorded as being at position –305 mm (–11.9 inches), but it was actually left at position +203 mm (+7.9 inches).
- d2 was reported as being at position +203 mm (+7.9 inches), but it was actually positioned at –305 mm (–11.9 inches).
- d2 was reported as being at position +305 mm (+11.9 inches), but it was actually positioned at –305 mm (–11.9 inches).

Screening techniques, along with a visual review of the screened data, made it quite easy (albeit time-consuming) to identify the vast majority of errors in the first two categories. The last category (with the missing minus sign) has already been changed through a global correction in the database. Therefore, this category was not reported in detail as were the two others. The first two categories of errors affected approximately 0.4 percent of the total volume of FWD data in the pre-autumn 1998 database. These errors were reported in Feedback Report RNS–3 in September 1999 (see appendix A).

Reportedly, the vast majority (135 out of 140) of the identified sensor positioning errors identified in Feedback Report RNS–3 have already been corrected in the level E load-deflection tables in the database. In fact, many of these errors were also identified through other means, as part of an independent global check for incorrect sensor configurations. The remaining five identified anomalies are presently being checked for correction, if necessary, in the appropriate database sensor configuration data tables.

LANE DESIGNATION ERRORS

Since the lane designations (e.g., F3, C1, J4) are manually input, it is not surprising that a limited number of lane designation errors were identified in the database. Examples of these included entering C4 instead of J4 on a jointed PCC section, or switching J4 and J5 at one of the tested joints. There were only about 350 instances of this type of error in the entire pre-autumn 1998 database, or less than 0.1 percent of the data. These errors were also reported in Feedback Report RNS–6 dated September 1999 (see appendix A).

RECORDING DATE ERRORS

In five instances, the same LTPP section day file was reopened on a second date of testing when it was not possible to complete testing of a given section during one day. As a result, only the *last* date of test was recorded in the day file, and therefore only this last date of test (even though two days of test actually occurred) was transferred to the level E database. These errors evidently occurred only five times in the entire pre-autumn 1998 database, thus affecting slightly less than 0.1 percent of the data in the database.

The reason this type of error occurred is a property of the Dynatest Edition 20 field program, which permits reopening of a data file (for example when an operator breaks for lunch and reopens a test section file afterward). However, when a given file is reopened on a different date, the first date is precluded (overwritten) by the second date, although the time stamps are still correct for both.

In each case when there should have been two separate test dates, the data records showing the incorrect dates were recommended for change and correction in the database in Feedback Report

RNS–6 (shown in appendix A). Further, in all but one of these five cases, the affected regional coordinators agreed to the recommended changes and carried them out in the load-deflection database, which has been updated accordingly. The one controversial case has since been reexamined, and the originally recommended date change in RNS–6 was verified and re-recommended for change in the database. This case concerned LTPP test section 10–0210 in the North Atlantic Region, where some of the date stamps on test date June 30, 1997, should read June 29, 1997.

DROP HEIGHT DESIGNATION ERRORS

In the drop height data field, the numbers 1, 2, 3, or 4 should appear, corresponding to one of the four possible drop heights of the Dynatest FWD equipment. However, in several instances, an X was placed in this field in the level E database. These instances were reported to FHWA in early 1999, and all Xs were duly changed to 1, 2, 3, or 4 in the database, as appropriate.

Before this error was corrected, some 0.3 percent of the FWD data in the database were affected.

OTHER POTENTIAL DATA ERRORS OR ANOMALIES

There were also a few other relatively minor types of errors or anomalies identified in the FWD load-deflection level E database during the data screening processes described above. For example, there were a handful of instances where the time of test was evidently edited in the regional office from what was recorded in the field, but only partially; the remaining data should also have been edited to make it consistent with the temperature measurements and/or with the sequence of other events in the field. When and if possible, all obvious errors noticed during the screening process were recommended for correction accordingly.

In a limited number of cases, the possibility (or even the probability) of somewhat vague errors or anomalies existed. However, when these errors were not obvious or certain, no changes or flags were recommended in the database.

Apart from the unbound material test data, approximately 1 percent of the FWD load-deflection database appeared to include data anomalies that could not be verified with certainty, because there was neither any supporting information nor a plausible explanation for the unusual data. These types of data anomalies are discussed in chapter 6 in a general manner; however, the notes or remarks that were created are presently not available to LTPP load-deflection database users. That information is associated with individual, comma-delimited data files, not the relational Microsoft Access® database utilized in the various versions of DataPave.

CHAPTER 6. NOTED ANOMALIES AND OTHER POTENTIAL DATA PROBLEMS

DATA SCREENING ANOMALIES OR SPURIOUS DATA

During the process of identifying the data errors described in chapters 3, 4, and 5, other potential errors or anomalies were also identified. In most cases, however, these anomalies could not be verified or rectified; thus, they were not recommended for specific changes in the database. These unverified errors or anomalies are discussed in this chapter, in one of the two following categories:

- General or global notes about the types of problems or spurious data encountered (some specific instances are also covered elsewhere in this report).
- Specific notes referring to each spurious day file (day file-specific notes only).

PRECAUTIONARY NOTES REFERRING TO THE FWD LOAD-DEFLECTION TABLES

Table 7 consists of a list of the most important, general data anomalies noted during the course of analyzing the FWD load-deflection data. Some of these anomalies have been addressed in the foregoing chapters as well.

Table 7. General data anomaly notes of unchanged records or files.

Note 1	In all cases where unbound material tests (designated as lane S∗ or G∗) were conducted, these data have not been recommended for changes or flags in the level E database. It should be noted that the quality and repeatability of this data is an order of magnitude or so poorer than the rest of the level E load-deflection data. Therefore, unbound material test data have not been as thoroughly screened as the remaining load-deflection data in the data tables.
Note 2	It is possible to interchange one dedicated FWD field computer for another, such as when there are two FWDs and corresponding system processors in the same region. This may or may not have occurred in practice; if so, the load and deflection readings will be affected to an unknown degree (possibly several percentage points), but such effects probably are not detectable using the available screening tools.
Note 3	In many cases, the configuration number indicates PCC joint testing positions (e.g., J4, J5, C4, or C5) as 0, 305, 305, 457, etc.; in each of these cases the value +305 denoted for d2 should be, or should already have been, changed to –305, corresponding to the position of the sensor behind the FWD loading plate.
Note 4	There were many stationing errors where the plus (+) or minus (–) sign was recorded and stored in the level E data tables opposite of what it should have been. Most, but probably not all, of these errors have been identified and recommended for change in the data tables.
Note 5	In Region 3, States 35 and 40 (New Mexico and Oklahoma), in many cases when PCC testing was conducted on different dates, there appear to be large deflection differences in the lane 1 tests from one test date to the next (up to a factor of 2 or 3, or more). Quite possibly, this could be due to liftoff or slab warping resulting from extreme thermal gradients. If so, this is a phenomenon worthy of further investigation and, possibly, altering testing protocols for jointed PCC pavement in some areas.

Table 7. General data anomaly notes of unchanged records or files (continued).

Note 6	In Region 2, on some of the SPS–5 sections denoted 27–050∗, it was noted that the variation from date-to-date in deflections was very large. This variation may in fact have been due to an error in section identification. However, it was not possible to determine the actual cause of this potential set of anomalies. Therefore, the FWD data associated with these SPS–5 sections have not been recommended for changes or flags in the level E database. However, such anomalies or potential site/section errors could be identified with certainty by installing a low-cost global positioning system on the affected FWDs for future testing.
Note 7	In Region 4, there are a large number of PCC joint efficiencies measuring well over 100 percent; however, only those over 113 percent were noted in a separate data table. None of these has been corrected, and no data have been removed or flagged in the level E data tables.
Note 8	In Region 3, there are a small number of PCC joint efficiencies measuring over 100 percent; however only those over 105 percent were noted in a separate data table. None of these has been corrected, and no data have been removed from the level E data tables.
Note 9	In Region 2, it appears that there are many cases where the PCC joint was placed between d3 and d4 instead of d1 and d3 as per protocol, for lane J4 tests. However, only the most extreme cases of these were noted in a separate data table. None of these has been corrected, and no data have been removed from the level E data tables.
Note 10	In Region 1, it appears that there are some cases where the PCC joint was placed between d3 and d4 instead of d1 and d3, for lane J4 tests. However, only the most extreme cases of these were noted in a separate data table. None of these has been corrected, and no data have been removed from the level E data tables.
Note 11	In Region 4, section 04–0502, on all six dates of testing there was a bizarre pattern of deflection development between dates. The FWD load-deflection table results are nevertheless possible; thus no errors have been reported, and no data have been corrected, removed, or flagged in the level E data tables.
Note 12	In Region 4, section 04–0509, on all seven dates of testing for this section (intensive rehabilitation: ~50.8-mm (2-inch) overlay), the data is somewhat peculiar. Nevertheless, since FWD testing was possibly (but not definitely) conducted on the correct test section before, during, and after rehabilitation given these strange results, no errors have been reported, and no data have been corrected, removed, or flagged in the level E data tables.
Note 13	In Region 4, section 06–b420, on all four dates of testing for this section there were many test points (whether J1, J4, J5 or J6, etc.) that show strange or bizarre deflections, such as nondecreasing, too large, or too small, etc. However, not all test points were unusual; thus no errors have been reported, and no data have been corrected or removed from the level E data tables except through other procedures mentioned in other sections of this report.
Note 14	In Region 4, section 08–0214, on all three dates of testing for this section, a plausible pattern of deflection development was noticed between test dates, but the magnitudes of the deflection readings were vastly different (by as much as a factor of 3). These seem unlikely, but since the results are possible, no errors have been reported, and no data have been corrected, removed, or flagged in the level E data tables.

Table7. General data anomaly notes of unchanged records or files (continued).

Note 15	In Region 4, section 08–0220, on all three dates of testing for this section, a plausible pattern of deflection development was noticed between test dates, but there were appreciable differences between dates, especially in the deflections between stations 100 and 350. Nevertheless, no errors have been reported, and no data have been corrected, removed, or flagged in the level E data tables.
Note 16	In Region 4, section 08–2008, on all dates of testing for this section, it appears that there may have been an overlay placed between May and October 1991, but the construction number remains the same throughout (CN = 1). This is probably (but not definitely) an error in the level E database value of CN, which should be considered in any subsequent data analyses conducted on the test section.
Note 17	In a handful of cases, it is possible that lane designation errors occurred during an entire day of testing, although this particular category of data errors was not specifically screened. One such instance (on two consecutive dates of test) was identified and corrected, as discussed in chapter 5 of this report.
Note 18	In the course of screening for FWD load-deflection errors and anomalies, it was noticed that some of the operator comments had not been uploaded to the database, while others were recorded for general DataPave or level E use. It is suggested that the remaining comments be uploaded together with the deflection data as both become available. Such comments often yield important information about data collection problems or anomalies that can be quite useful to the analyst.

CHAPTER 7. SUGGESTED COMPUTED PARAMETERS AND FWD TESTING PROTOCOLS

THE INITIAL WORKING DATA FILES FOR THE PROJECT

As mentioned near the beginning of this report, the originally provided database files were reorganized to facilitate further analyses. Specifically, day files were created under directories organized by region and test section; these files consisted of all the data for each date of test at each LTPP section. These day files were changed in accord with the findings of this study to include the deletions, changes, and notes reported above. All of these files were written to a computed parameter data CD, which consisted of normalized and averaged FWD load-deflection data, with data errors and anomalies identified, changed, or deleted from the files as appropriate.

THE MODIFIED (COMPUTED PARAMETER) INDIVIDUAL DATA FILES

As mentioned previously, each day file was identified by a six-character date (yymmdd). After each date, in the seventh character of the file name, the letter "n" or "m" was employed. The letter "n" stands for normalized, while "m" stands for modified after normalization. Finally, each normalized and/or modified day file has the extension "∗.txt" since these are comma-delimited files. Occasionally, "u" or "x" was used instead of the usual "n" or "m." These two letters denote that a note only is present, with no data. Such notations are further explained below.

The "n" files denote those day files that have been screened for inconsistent basin type load-deflection errors. They have been normalized to the target load levels for each drop height, while each line or record represents the average of the deflection readings for a given test point and drop height. The field for drop sequence number has been replaced with a field indicating the number of drops (1, 2, 3, or 4) used to create the averages. The "n" files have no other changes or notes attached. The "m" files denote that some additional change or changes have taken place. In all these cases, there is a note in the *last* record of the "m" file that explains the changes or deletions (in some cases) or warns the user of potential problems (in other cases). These pre-autumn 1998 data files presently exist on a single data CD (approximately 100 megabytes).

However, it was decided that these files would not be incorporated into the LTPP database. Therefore, no computed parameters of pavement deflections exist at this time in the LTPP database. It is, however, still possible that the "n" files could eventually be consolidated into database tables so that they are available for general use.

FWD TEST PROTOCOL RECOMMENDATIONS

Based on the findings of this report and other considerations, the following LTPP FWD testing procedure changes were recommended in 1999:

1. Install the Dynatest Edition 25 Field Program, in lieu of the currently employed Edition 20.
2. Utilize all nine available deflection sensors, in lieu of the currently employed seven sensors.
3. Place sensors 1 through 9 permanently at the following positions: 0, 203, 305, 610, 914, 1219, 1524, 1829, and –305 mm, respectively. These positions will permit all types of tests with no maneuvering of sensors. The corresponding U.S. customary sensor positions, in inches, are: 0, 8, 12, 18, 24, 36, 48, 60, and –12, respectively.

4. With a simple software change to Edition 25, request Dynatest to allow for the recording of *both* the infrared (IR) pavement surface temperature at the time the F1 key is pressed, and also at the time a test sequence ends; the current procedure only records the latter measurement. One of the many available fields in the comma-delimited "Station" line of Edition 25 can be used for the extra temperature value (along with the usual time-of-departure IR temperature reading).
5. Continue utilizing three seating drops, as previously, at drop height 3; however, record the peaks of these three seating drops for potential use in analyzing the pavement's hardening or softening properties, which may be related to pavement performance.
6. It is adequate to utilize only *three* drop heights for all types of bound-layer tests, whether PCC or AC, and for all types of LTPP testing, whether General Pavement Studies (GPS), Specific Payment Studies (SPS), or the Seasonal Monitoring Program (SMP). These drop heights should be 2, 3, and 4, or approximately 9, 12, and 16 kips, respectively.
7. It is adequate to utilize only *three* drops per drop height for all types of bound-layer tests, whether PCC or AC, and for all types of LTPP testing, whether GPS, SPS, or SMP.
8. It is adequate to store only *one* full load-deflection time history for each test point, for all types of bound layer tests, whether PCC or AC, and for all types of LTPP testing, whether GPS, SPS, or SMP. If it is not possible to record more than one full time history per test point, this full time history should be the last drop at the highest utilized drop height.
9. Utilize the same spacing between test points as is currently used for the various types of experiments (GPS, SPS, and SMP).
10. Do not eliminate or delete FWD operator comments from the level E database.
11. Make sure both IR temperatures (at factory calibration settings) and manual temperatures are monitored according to the original protocols, and that the temperature measuring equipment is operating properly. Reemphasize the importance of correct protocol in measuring indepth temperatures.
12. Furnish the regions with the transformed basin or SLIC procedure software for all types of data storage files. This screening tool should help correct or eliminate data errors well *before* they reach level E in the database, whether these data errors may be in the form of misplaced sensors, faulty sensors, or sensor holders.
13. Emphasize the importance of checking sensor spacings and the stability of the sensor holders, magnets, and other equipment (including the center sensor) prior to testing at each LTPP test section.
14. All other current FWD testing and QA/QC protocols and procedures—*especially those involving accuracy of actual sensor positions and the correct method of conducting pavement temperature measurements*—should remain the same.

Further, an analysis was conducted to develop a procedure to determine if more frequent LTPP testing should be conducted as a pavement ages and exhibits more distress. The approach was to use a representative measure of the deflection basin, adjust this measure for pavement temperature, and determine whether definitive trends in the selected deflection measure exist.

The following specific analysis approach was used:

1. After a review of various deflection basin measures, it was decided to use the AREA measure to represent the overall characteristics of the deflection basin. The AREA measure is a calculation of the normalized area of a deflection basin. Facilitating the use of the AREA measure was the fact that a temperature adjustment procedure particularly pertinent to the

AREA measure was available. The AREA, using U.S. customary units, has traditionally been defined as shown by the equation in figure 5:

$$AREA = 6/d(0) * (d(0) + 2d(12) + 2d(24) + d(36))$$

where: $d(n)$ = deflection at n inches (n * 25.4 mm) from the center of the load plate

Figure 5. Equation. AREA.

A list was developed of GPS–1 and GPS–2 test sections that had at least four different times (nonseasonal) of deflection testing between 1989 and 1998. Ten of these test sections were randomly selected for further analysis.
The AREA values were determined for each F3 test point (wheelpath testing at 7.6-m (25-ft) test intervals).
The average middepth temperatures during the approximately 1 hour of wheelpath testing were established, for each test visit and for each of the 10 sections.
The basin adjustment factor (TAF) for the AREA parameter was established using the procedure described in a previous FHWA study, *Temperature Predictions and Adjustment Factors for Asphalt Pavement*.[2] Although the TAF is a function of the AC layer thickness and the latitude of the test section, it typically ranges in almost a linear manner from about 0.90 at 0 ºC (32 ºF) middepth temperature to about 1.1 at 40 ºC (104 ºF) middepth temperature, using the reference middepth temperature of 20 ºC (68 ºF). The temperature adjusted AREA is then given by the equation in figure 6:

$$AREA\ (@20\ ^{\circ}C) = AREA\ (@\ test\ temperature\ t) * TAF\ (@\ test\ temperature\ t)$$

Figure 6. Equation. AREA (@ 20 ºC).

All AREA values determined in step 3 were adjusted to account for the middepth pavement temperature as shown in step 5. The adjusted AREA values are listed in table 8.

A review of the results shown in table 8 indicates no definitive trends in average AREA values with time for the ten sections used in the analysis. Therefore, no specific recommendations can be provided at this time for considering changes in the frequency of deflection testing. Also, no acceptable procedures presently exist to adjust the maximum deflections for temperature at the time of test, although this may be possible in the near future. Finally, it may be necessary to include sections exhibiting significant cracking and/or rutting distress in the study sample, since it is possible that the deflections do not change appreciably until some pavement distress ensues.

The recommendations shown above were reported in 1998. Most (but not all) of these recommendations have since been implemented in connection with FWD upgrades, annual equipment servicing, and other events, and the FWD deflection testing protocols have been changed accordingly, where appropriate.

Table 8. Deflection testing frequency analysis data.

Test Section	Test Date	Average AREA	AREA Standard Deviation	Test Temp. (°C)	Temp. Adjstmnt. Factor	Adjusted AREA	Max. Deflection μm
1–1019	11/13/89	19.06	1.01	22.8	1.02	18.69	245
	11/26/90	19.27	0.89	20.0	1.00	19.27	241
	7/28/92	15.94	0.72	36.7	1.09	14.62	346
	1/23/98	20.10	1.48	14.4	0.97	20.72	334
13–4112	9/20/89	23.52	1.34	32.2	1.07	21.98	137
	7/12/94	21.19	1.05	31.7	1.07	19.80	145
	3/14/95	25.65	1.28	21.7	1.01	25.40	107
	4/23/98	25.82	1.68	23.9	1.02	25.31	94
22–3056	7/17/90	25.96	1.50	26.7	1.04	24.96	98
	3/30/92	27.34	1.14	20.0	1.00	27.34	104
	11/7/94	25.96	1.55	21.1	1.01	25.70	117
	9/16/98	24.74	1.71	18.9	1.05	23.56	133
25–1003	6/19/89	19.93	0.86	28.3	1.04	19.16	257
	6/10/91	19.44	0.88	28.9	1.05	18.51	252
	10/23/96	21.81	0.92	12.2	0.96	22.72	260
	6/16/98	20.80	0.92	20.6	1.01	20.59	272
28–3089	10/10/90	26.01	1.48	18.9	0.99	26.27	94
	11/19/92	25.74	2.15	13.9	0.97	26.54	111
	11/28/95	26.00	2.98	12.2	0.96	27.08	118
	7/9/98	22.99	1.87	18.9	0.99	23.22	147
34–1031	5/8/89	20.81	2.21	16.1	0.98	21.23	265
	7/8/91	18.64	1.85	26.1	1.03	18.10	283
	10/26/95	19.68	1.62	14.4	0.97	20.29	295
	8/1/96	19.80	1.21	25.0	1.03	19.22	215
42–1597	8/15/89	18.11	0.67	28.9	1.05	17.25	265
	5/7/90	20.63	0.66	17.2	0.98	21.05	224
	6/7/94	16.84	0.71	37.8	1.10	15.31	393
	9/13/95	19.42	1.38	26.1	1.03	18.85	295
	9/2/97	18.07	1.25	30.0	1.05	17.21	376
47–1029	4/20/89	22.89	0.85	19.4	0.99	23.12	63
	8/20/92	20.93	0.77	27.2	1.04	20.13	81
	5/23/95	20.20	0.73	28.3	1.04	19.42	85
	6/9/98	21.41	1.10	23.9	1.02	20.99	84
48–1048	6/16/89	22.80	1.89	31.1	1.06	21.51	175
	11/14/91	27.72	0.69	15.6	0.98	28.29	129
	11/15/94	27.05	1.05	16.7	0.98	27.60	143
	6/6/96	23.70	1.49	31.1	1.06	22.36	180
48–3559	3/22/90	24.15	1.47	21.7	1.01	23.91	130
	9/6/91	22.77	1.68	27.8	1.04	21.89	147
	4/18/96	23.55	1.48	28.3	1.04	22.64	158
	3/27/98	24.35	1.44	27.2	1.04	23.41	152

CHAPTER 8. SUMMARY AND CONCLUSIONS

This report presents the results of an indepth assessment of the pre-autumn 1998 LTPP load-deflection data. Several categories of errors and anomalies were identified, and the deflection data and associated parameters were recommended for flagging or correction, as appropriate.

The study resulted in an LTPP product called the transformed deflection basin procedure, also known as SLIC, that can identify sensor spacing errors or (potentially) erroneous sensor output. The SLIC procedure was also utilized in-house to facilitate the analysis of the deflection data as outlined in this report. This procedure has tremendous potential for routine use as one of the quality control checks by the FWD operator or the engineer reviewing the deflection data. It is recommended that the SLIC procedure be developed further as a user-friendly QC package that can be used in the LTPP program as well as by other highway agencies.

APPENDIX A. VARIOUS FEEDBACK REPORTS SUBMITTED TO FHWA

On the following pages, Feedback Reports RNS–2M, RNS–3, RNS–4M, RNS–5, RNS–6, and RNS–7 are reproduced (without their attachments).

TO: Long-Term Pavement Performance Program
HRDI–13
6300 Georgetown Pike
McLean, VA 22101–2296
Facsimile: (202) 493–3161
Email: *LTPPINFO@fhwa.dot.gov*

LTPP Data Analysis/Operations Feedback Report

Report No.: RNS–2M

Date: 28 December 2000

Submitted by: R. N. Stubstad, E. Lukanen and L. Clevenson

Subject: LTPP FWD Load-Deflection Configuration Data in the Database

Situation:
For several distinct time periods for certain FHWA-owned and non-owned FWDs, several of these units were used with the deflection sensors placed incorrectly along the raise-lower bar. These non-protocol sensor spacings are still recorded as being in the protocol positions in the level E database. The measured deflections appear to be correct; however large errors in (for example) backcalculation will occur if the actual sensor positions are not recorded and used together with the measured deflections. The attached letter outlines the correct positions of the sensors in a list of instances were there was incontrovertible evidence to support the newly reported sensor positions. This new list is a slight modification of the RNS–2 Feedback Report submitted during 1999. This Feedback Report supercedes RNS–2, called RNS–2M (modified).

Recommended Action:
Revise the sensor configuration table in the database to reflect the actual, not protocol, sensor positions, as outlined in the attached letter. (NOTE: The sensor position table is not easily accessible when the FWD load-deflection data are queried in DataPave 2.0.)

Distribution			**Urgency** (check one) Resolution needed by: ❑ _______________ (Date) ❑ Next upload of affected data
Referred to:	**Assigned to:**	**Information Copies to:**	
			Comments:

Action to be Taken: As recommended______ As outlined below

Date assigned:

Date due:

Findings/Actions Taken:

Date completed:

Attach additional pages as necessary to describe situation, recommended action, and actions taken.

TO: Long-Term Pavement Performance Program
HRDI–13
6300 Georgetown Pike
McLean, VA 22101–2296
Facsimile: (202) 493–3161
Email: *LTPPINFO@fhwa.dot.gov*

LTPP Data Analysis/Operations Feedback Report

Report No.: RNS–3

Date: 15 September 1999

Submitted by: R. N. Stubstad, E. Lukanen, S. Tayabji and L. Clevenson

Subject: More LTPP FWD Load-Deflection Configuration Data Errors in Database

Situation:
In addition to the long-term sensor positioning errors outlined in Feedback Report RNS–2 (later RNS–2M), there are approximately 140 instances where a single set of data (non-time dependent) had one reported set of sensor positions in the configuration records, while in the field clearly another set was used. In most (but not all) cases, these errors were related to joint testing (J4, J5, C4 & C5). Some of these "instances" are overlapping, for example a J4 and J5 set of data in the same "day" file are both identified, so the number "140" is, to a certain extent, misleading. These are presented in a region-by-region format. Please note that the categorical errors—where d2 was positioned at –305 mm for joint tests, yet listed as +305 mm (this occurred quite frequently)—are not identified herein, since a global change in the database has reportedly been used to correct this error.

Recommended Action:
Revise configuration tables in the database to reflect the actual, not protocol, sensor positions, as identified on the enclosed diskette and outlined in the attached letter.

Distribution			Urgency (check one)
Referred to:	**Assigned to:**	**Information Copies to:**	Resolution needed by: ❑ ______________ (Date) ❑ Next upload of affected data
			Comments:

Action to be Taken: As recommended______ As outlined below

Date assigned:

Date due:

Findings/Actions Taken:

Date completed:

Attach additional pages as necessary to describe situation, recommended action, and actions taken.

TO: Long-Term Pavement Performance Program
HRDI–13
6300 Georgetown Pike
McLean, VA 22101–2296
Facsimile: (202) 493–3161
Email: *LTPPINFO@fhwa.dot.gov*

LTPP Data Analysis/Operations Feedback Report

Report No.: RNS–4M

Date: 30 September 2001

Submitted by: R. N. Stubstad, E.O. Lukanen and M.L. Clevenson

Subject: Inconsistent Deflection Basins of FWD Load-Deflection Records in the Current Data Tables.

Situation:
Feedback Form RNS–4 (dated September 1999) had listed a total of 7,045 individual FWD records (or lines) of data in the ∗.M06 files reported to have significantly large "random errors" or inconsistent deflection basins in the pre-autumn 1998 database. Meanwhile, all of the records that were associated with non-joint and non-J6 FWD test results and having one or more increasing deflections, as a function of distance from the loading plate, have now been flagged, in Column 24 (or X) in the current LTPP database, with a numeral "1". The entire original list of 7,045 records has now been re-screened. Some of these records, where a potentially correct deflection basin had been previously identified as containing a random error, or if a previously identified record was not clearly inconsistent, are *not* identified in this Feedback Report. Also, none of the lines with increasing deflections is included in this list. As a result, a new list of 2,642 records of inconsistent deflection basins has now been re-identified for flagging in the FWD database. Please note that some of these 2,642 records, where single deflection readings were excessively large or small, may have already been altered in the current LTPP database using a blank field in the appropriate deflection column. Also please note that a few of these records may have already been deleted from the database, as previously suggested.

Recommended Action:
In Column 24 (or X) of the appropriate records in the FWD load-deflection database tables, please place a flag numeral "2" to indicate an inconsistent deflection basin, for reasons other than an increasing deflection basin (already flagged as a "1"), as per the accompanying Excel Spreadsheet "*Inconsistent Deflection Basins – Sept. 2001.xls.*" The data in the single Excel worksheet entitled "Feedback Summary" are organized by LTPP region. The first 23 fields in each of these records (or lines) are organized in a manner similar to the original ∗.M06 files obtained directly from the database (Data Release 9.0, dated 11/23/98). Additionally, in cases where any of the identified records, or any other record in the current database, already contains one or more deleted deflection readings, please place a "2" in Column 24 (or X) as well. This will assist the FWD load-deflection data analyst in identifying potentially inconsistent *or* incomplete deflection basins when carrying out bulk data processing. A letter explaining the Excel Spreadsheet in more detail is attached.

<table>
<tr><th colspan="3">Distribution</th><th rowspan="2">Urgency (check one):
Resolution needed by:
❑ _______________ (Date)
❑ Next upload of affected data</th></tr>
<tr><th>Referred to:</th><th>Assigned to:</th><th>Information Copies to:</th></tr>
<tr><td></td><td></td><td></td><td>Comments:</td></tr>
<tr><td colspan="4">Findings/Actions Taken:</td></tr>
<tr><td colspan="3"></td><td>Date completed:</td></tr>
</table>

Attach additional pages as necessary to describe situation, recommended action, and actions taken.

TO: Long-Term Pavement Performance Program
HRDI–13
6300 Georgetown Pike
McLean, VA 22101–2296
Facsimile: (202) 493–3161
Email: *LTPPINFO@fhwa.dot.gov*

LTPP Data Analysis/Operations Feedback Report

Report No.: RNS–5

Date: 22 September 1999

Submitted by: R. N. Stubstad, E. Lukanen, S. Tayabji and L. Clevenson

Subject: Incorrect Duplicate Data and Other Error Lines of FWD Load-Deflection Data in Database

Situation:
There are approximately 12,000 individual records (or lines) of data in the ∗.M06 files, organized by region, test site and date of test, which are erroneous. The two main reasons for this are: 1) duplicate lines of data with incorrect time stamps or other errors in data entry, and 2) five occurrences of an entire day's FWD tests conducted at the wrong LTPP test site. Other reasons include systematic deflection errors plus a few other infrequently occurring errors. The records that need to be deleted are organized as outlined in the attached letter. The approximately 12,000 records recommended for deletion from the database corresponds to some 0.28% of the total volume of FWD load-deflection data.

Recommended Action:
From the ∗.M06 files in the database, delete the various records of data from each LTPP Region as outlined in the attached letter and as presented in the enclosed comma delimited files of erroneous data records.

Distribution		
Referred to:	**Assigned to:**	**Information Copies to:**
LTPP	TSSC 10/99	
	RCOCs 1/01	

Urgency (check one)
Resolution needed by:
❑ _______________ (Date)
❑ Next upload of affected data

Comments:
Resolved for TSSC. Refer to RCOCs for action as recommended by TSSC.

Action to be Taken: As recommended______ As outlined below

Date assigned:
1/11/01

Date due:
3/23/2001

Findings/Actions Taken: Actions have been taken and the issues have been resolved.

Date completed: 1/24/01

Attach additional pages as necessary to describe situation, recommended action, and actions taken.

TO: Long-Term Pavement Performance Program
HRDI–13
6300 Georgetown Pike
McLean, VA 22101–2296
Facsimile: (202) 493–3161
Email: *LTPPINFO@fhwa.dot.gov*

LTPP Data Analysis/Operations Feedback Report

Report No.: RNS–6

Date: 24 September 1999

Submitted by: R. N. Stubstad, E. Lukanen, S. Tayabji and L. Clevenson

Subject: Data Input (Individual Cell) Errors in the Load-Deflection Records in Database

Situation:
There are approximately 7,600 individual cells contained in about the same number of records (or lines) of data in the ∗.M06 files, organized by region and error type, which are erroneous. Most of these errors were manual data entry errors, such as Lane or Station Number. In many other instances, the date of test was incorrect due to reopening of an existing FWD data file on two successive dates. Finally, some time stamps were also incorrect (usually by one hour). The cells of data that need to be changed are organized as outlined in the attached letter. The approximately 7,600 cells recommended for change in the database affects some 0.17% of the total volume of FWD load-deflection data contained therein.

Recommended Action:
In the ∗.M06 files in the database, change the various records of data in each LTPP Region, as outlined in the attached letter and as presented in the 15 enclosed comma delimited files of erroneous data records.

Distribution		
Referred to:	**Assigned to:**	**Information Copies to:**
LTPP	TSSC	
	RCOCs 01/11	

Urgency (check one)
Resolution needed by:
❑ _______________ (Date)
❑ Next upload of affected data

Comments:

Action to be Taken: As recommended __X__ As outlined below

Date assigned:
1/11/01

Date due:
3/23/01

Findings/Actions Taken: Action has been taken and the issues have been resolved.

Date completed: 1/24/01

Attach additional pages as necessary to describe situation, recommended action, and actions taken.

TO: Long-Term Pavement Performance Program
HRDI–13
6300 Georgetown Pike
McLean, VA 22101–2296
Facsimile: (202) 493–3161
Email: *LTPPINFO@fhwa.dot.gov*

LTPP Data Analysis/Operations Feedback Report

Report No.: RNS–7

Date: 30 September 2001

Submitted by: R. N. Stubstad, E.O. Lukanen and M.L. Clevenson

Subject: Use of Column X or 24 in the FWD Load-Deflection database Data Tables.

Situation:
Recently, Column 24 (or X) in the current LTPP database has been used to place a numeral "1" in cases of increasing deflections for non-joint associated FWD test results. This concept is expanded through the use of this column for a series of deflection basin codes, or warning flags. Two possible alternatives are:

	Code Description	Numeric Code	Letter Code
a)	Increasing deflections (for non-jointed tests)	1	I
b)	Other inconsistent basin data (re. RNS–4M)	2	B
c)	Non-protocol sensor positions (re. RNS–2M)	3	P
d)	Other non-protocol but database recorded sensor positions	3	P
e)	Data evidently from incorrect test section (re. RNS–5)	4	S

Recommended Action:
In Column 24 (or X) of the appropriate records in the FWD load-deflection data tables, please place flags in the form of deflection basin or sensor position codes, as noted above and expanded upon in the accompanying cover letter. Note: A numeral "1" is already present in the database load-deflection data tables.

Distribution		
Referred to:	**Assigned to:**	**Information Copies to:**

Urgency (check one):
Resolution needed by:
❑ _______________ (Date)
❑ Next upload of affected data

Comments:

Action to be Taken: As recommended______ As outlined below

Date assigned:

Date due:

Findings/Actions Taken:

Date completed:

Attach additional pages as necessary to describe situation, recommended action, and actions taken

APPENDIX B. SEMIAUTOMATIC SLIC PROCEDURE FOR FWD DATA SCREENING

The original SLIC method for finding sensor-positioning errors was a manual-visual examination of the transformed plot of a deflection basin. This visual method graph plotted the natural logarithm of the negative of the natural logarithm of the normalized deflections (on the vertical y-axis) versus the natural logarithm of the sensor position (on the horizontal x-axis). These graphs were very close to linear, but often with a slight downward concavity, when the sensor positions were correctly reported. The SLIC graphs shown in appendix C through L show marked departure from this typical pattern when sensors are not positioned as reported.

The first attempt at automating the detection of sensor-positioning errors used multiple linear regression to fit a quadratic curve (second degree polynomial) of ln(offset), y, to ln(-ln(normalized deflection)), x. The reason for reversing the axes was that we wanted to predict the value of the ln (offset) from the resulting second-degree equation. To try to go the other direction was sometimes impossible because the quadratic equation that was fit, a concave down parabola, might not reach the y-value corresponding to sensor 7. There was also too much bias and variation in this method when the equation could be solved.

The regression would always utilize the center deflection for normalizing, and five other points, but would leave out the point corresponding to the sensor in question. Then the position of the sensor in question would be predicted from its (normalized) deflection using the best-fitting curve to the other points. The predicted values of the sensor position would be plotted as a time series using all the test dates for one FWD. Then the plots would be examined (visually) for any consistent sequence of unusual values. This method was successful at finding the errors previously reported. However, there was a bias in the predicted results for sensor 7, and a model that eliminated that bias was found. The newer model also reduced the variation in the predicted results. This newer version used a model of the form shown in figure 7 ($|nd|$ represents normalized deflection):

$$\text{Offset} = a + b\,(\ln(|nd|))^{d} + c\,(\ln(|nd|))^{e} \;(+\text{ residual})$$

Figure 7. Equation. Offset, with exponents d and e.

The exponents, *d* and *e*, had to be selected before running any multiple regression. A dataset where no previous errors had been found was used to select the values of *d* and *e*. A program was written to try many values of *d* and *e* and select the values that predicted a particular sensor with little or no bias and the least variation. For the prediction of sensor 7, for example, these values for *d* and *e* are 0.6 and 2.2, respectively. The procedure also examined how many sensors to use, and the optimal number for sensor 7 was four, using the points corresponding to sensors 3 through 6. Apparently the simple curves investigated are not quite adequate to describe the entire (transformed) deflection basin. To estimate where a particular sensor was on a given test date, the entire set of data for that day was averaged, and then a multiple linear regression was run. For example, to estimate where sensor 7 on FWD number 131 was positioned on August 12, 1998, the average deflections on that day were calculated as shown in figure 8.

D1	D2	D3	D4	D5	D6	D7
319	306	296	278	258	215	138

Figure 8. Chart. Average deflections, FWD #131, August 12, 1998.

The normalized deflections are: 306/319 = .959, 296/319 = .928, etc. (Note that minor discrepancies may be due to rounding; the D1 deflection of 319 is really 319.220031738281, and all calculations used all available digits.) These values are converted to absolute natural logarithms, and then raised separately to the powers 0.6 and 2.2. For example, for the third normalized deflection 0.9280, its natural logarithm is negative 0.0747, producing an absolute value of 0.0747, and the two powers of 0.6 and 2.2 of this number are 0.2109 and 0.0033. Then the first point, corresponding to the values for sensor 3 in the multiple linear regression, is determined according to the formula in figure 9.

$$(y, x_1, x_2) = (\text{sensor position}, (\ln(|nd|))^{0.6}, (\ln(|nd|))^{2.2})$$

Figure 9. Equation. y, x_1, x_2.

For the present example, the result is (12, 0.2109, 0.0033). Similar values are found for sensors 4, 5, and 6, and then a multiple linear regression is fit to find the values of *a*, *b*, and *c* to minimize the sums of squares, as shown in the equation given in figure 10.

$$(y - (a + bx_1 + cx_2))^2$$

Figure 10. Equation. a, b, c.

The spreadsheet calculations would then look like the data presented in table 9.

Table 9. Initial SLIC procedure calculations for sensor 7.

Sensor	Mean Defl.	Norm.Defl.	|ln(nd)|	|ln|(nd)^0.6	|ln|(nd)^2.2
1	319	1	–	–	–
2	306	0.959933	0.0409	0.1468854	0.0008822
3	296	0.927981	0.0747	0.2109341	0.0033256
4	278	0.871092	0.138	0.3047488	0.012817
5	258	0.808533	0.2125	0.3948721	0.0331391
6	215	0.673987	0.3945	0.5723452	0.1292447
7	138	0.432116	0.8391	0.9000702	0.679746

Recall that sensor 2 data weakens the accuracy of the prediction of sensor 7, on average, and that sensor 7 data would be left out of the model that predicts the position of sensor 7. So a multiple linear regression would be fit as shown in table 10:

Table 10. Final SLIC procedure calculations for sensor 7.

Sensor	y	x1	x2
3	12	0.2109341	0.0033256
4	18	0.3047488	0.012817
5	24	0.3948721	0.0331391
6	36	0.5723452	0.1292447

This was done, and the results are shown in table 11.

Table 11. Regression results, sensor 7.

Regression Statistics	
Multiple R	1
R Squared	1
Adjusted R Squared	1
Standard Error	0.0662
Observations	4

ANOVA

	df	*SS*	*MS*	*F*
Regression	2	314.99561	157.49781	####
Residual	1	0.0043885	0.0043885	
Total	3	315		

	Coefficients	*Standard Error*	*T Stat*	*P-value*
Intercept	–1.549	0.2199251	–7.04254	0.09
x1	64.021	0.8377741	76.418037	0.01
x2	7.0493	2.233105	3.1567421	0.2

Then the values of *a*, *b*, and *c* can be (electronically) read from the output as –1.549, 64.021, and 7.0493, and the values of x1 and x2 for sensor 7 used to predict the position of sensor 7 as –1.549 + 64.021*.9000702 + 7.0493*0.679746. This value, 60.866, is the predicted value of the sensor 7 offset (in inches). This procedure was found to produce predictions that averaged close to 152.4 centimeters (cm) (60 inches) on datasets with no previously found error and with the least variation about this expected value. However, as can be seen in the graphs in appendices C through L, there is still some scatter, mostly due to the fact that an extrapolation somewhat far from the existing points is required. In the graphs that depict the time series of predictions of D7, found in appendices C through L, this prediction would correspond to exactly one point in graphs of D7 predictions for a particular FWD. The value of R^2, in this case so close to 1 that it is rounded to 1, also would be graphed as one point in the appropriate graph of R^2.

The entire procedure was repeated for sensor 2 predictions also, except that the model that best predicted 20.32 cm (8 inches) for sensor 2, was revised as shown in figure 11.

$$\text{Offset} = a + b\,(\ln(|nd|))^{0.9} + c\,(\ln(|nd|))^{2.2}.$$

Figure 11. Equation. Offset, sensor 2.

That is, only the value of d had to be changed, from 0.6 to 0.9, while the value of e remained at 2.2. As in the case of sensor 7, this work was based on a dataset believed to be error-free from previous work. The remainder of the procedure was identical, including the choice of an optimal set of data for predicting sensor 2, which also was the four closest sensors, sensors 3 through 6.

APPENDIX C. FWD SN #129, NOVEMBER 3, 1995–APRIL 14, 1996

This previously reported sensor position error was also identified using the automated version of SLIC (see appendix B). This procedure incorporated a model that was specifically chosen to predict the position of sensor 7 with a close to zero overall bias and the best possible precision. The first graph shown in this appendix (figure 12) is a plot of all the SN #129 d7 sensor position predictions during 1995 and 1996 for lane 1, drop height 4 FWD tests.

In figure 12, it can be seen that the average prediction for this 2-year period was around 152.4 cm (60 inches), as expected. The predictions are somewhat scattered due to the relatively large distance between d6 and d7. However, during the period of time in question (November 3, 1995–April 14, 1996), the average predicted position of d7 is clearly around 121.9 cm (48 inches) (average SLIC prediction for all flagged test dates = 123.2 cm (48.5 inches)). In fact, a sensor holder was positioned at 121.9 cm (48 inches).

The second figure in this appendix (figure 13), clearly shows that the SN #129 predicted positions for sensor 7 in the fall of 1995 are extreme outliers relative to the predicted positions for sensor 7 when other (correctly configured) FWDs are used. For the six test sections shown (from two different FWDs), the average predicted position of d7 was 157 cm (61.8 inches), while the average prediction for SN #129 during the period of time in question was 124.7 cm (49.1 inches).

In the two following figures (see figures 14 and 15), the same results are shown graphically, with the lines and data points labeled 11/9/1995 showing the SLIC plot for d7 in both its actual (121.9 cm (48 inches)) and protocol but incorrect (152.4 cm (60 inches)) offset position. The portions of the 11/9/1995 lines that are parallel to the rest of the protocol position data are the correct plots, with d7 set at 121.9 cm (48 inches).

Because of this information, and the other sensor position information supplied to FHWA, it can be concluded with certainty that d7 was *not* positioned correctly at 152.4 cm (60 inches); rather it was positioned at 121.9 cm (48 inches) (or very close to 121.9 cm (48 inches)) on FWD SN #129 between November 3, 1995, and April 14, 1996.

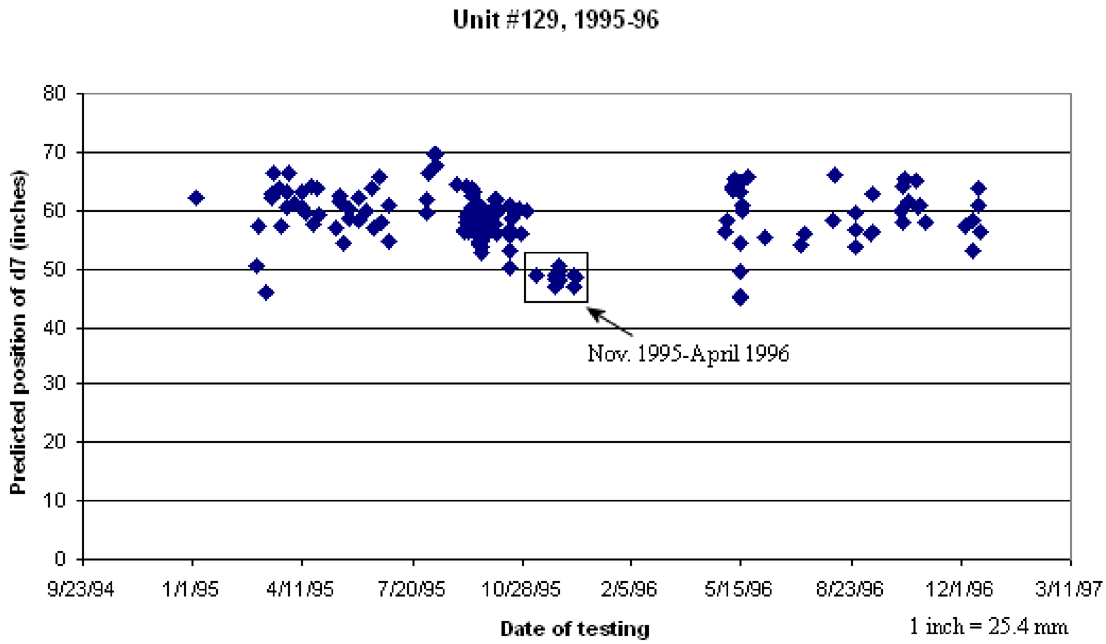


Figure 12. Graph. Predicted position of d7, unit #129, 1995–96.

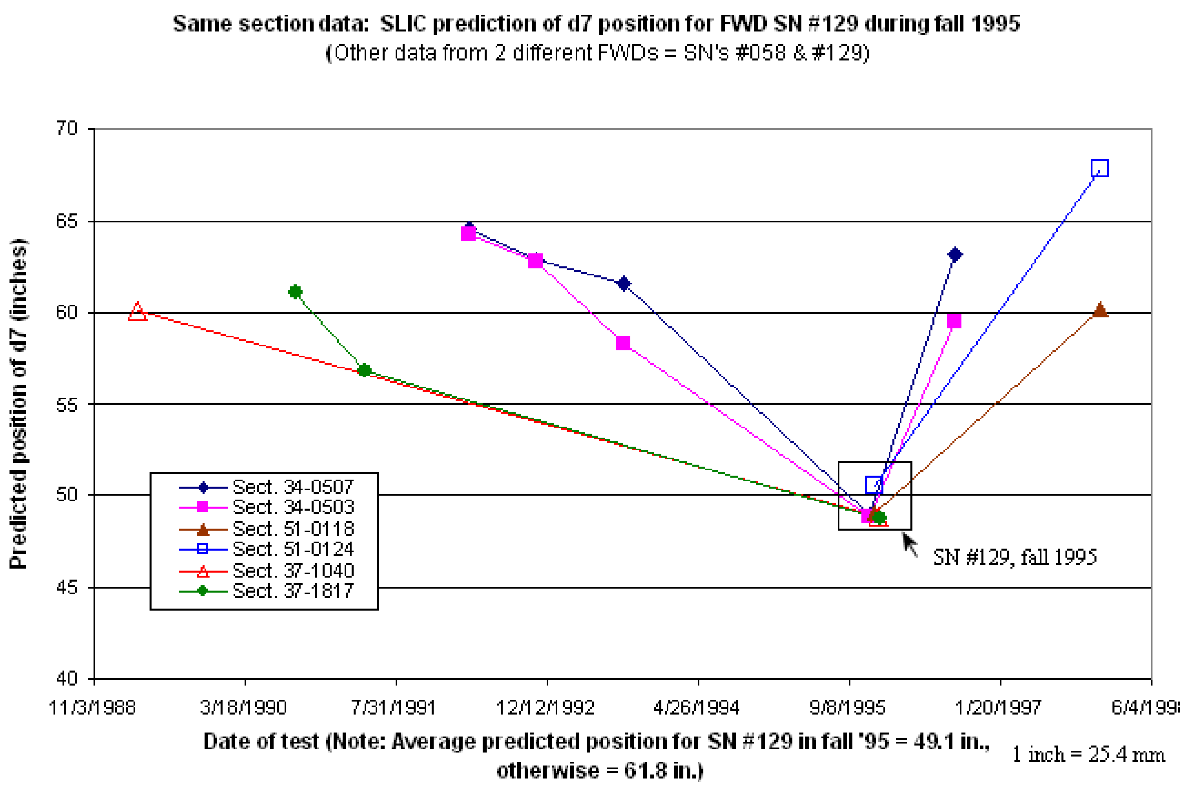


Figure 13. Graph. Same section data for d7 position, two different FWDs.

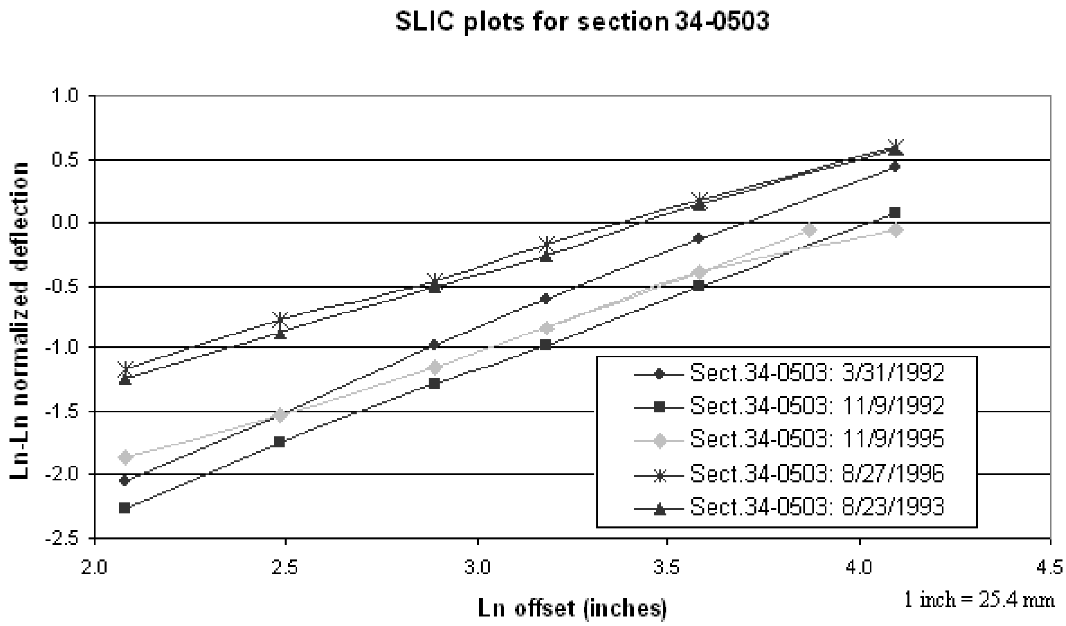


Figure 14. Graph. SLIC plots for section 34–0503 including unit #129, November 1995.

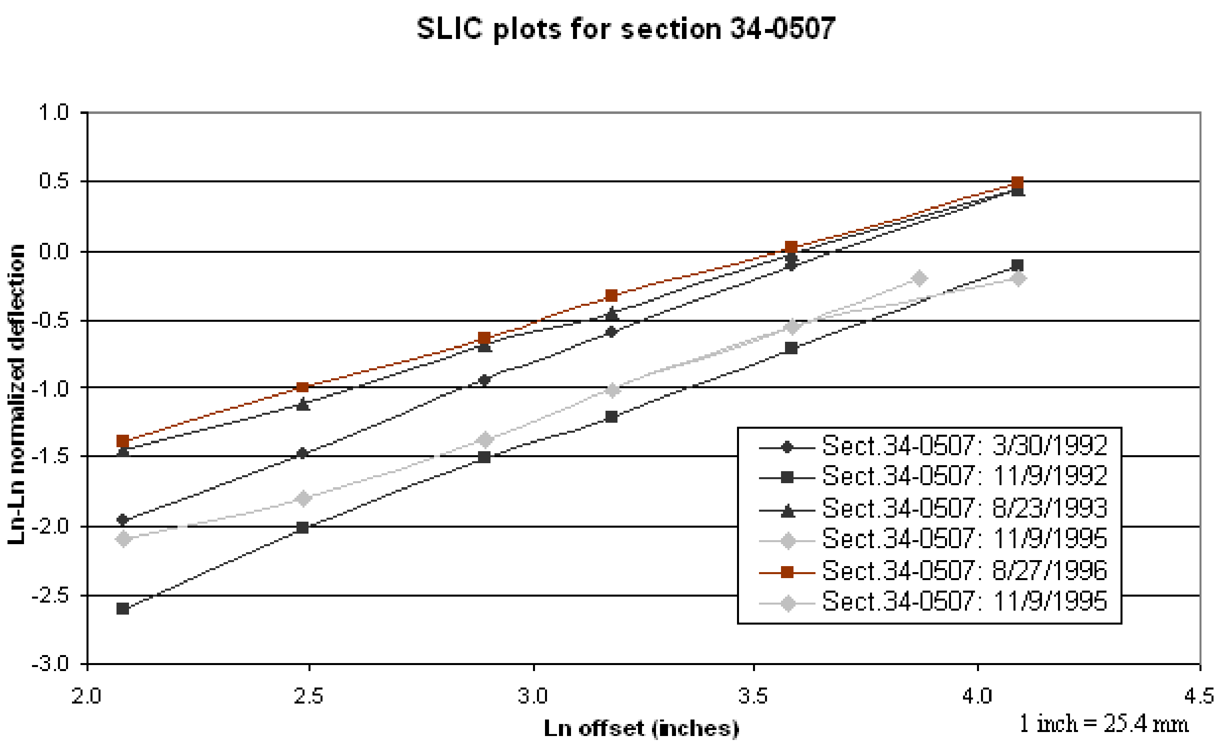


Figure 15. Graph. SLIC plots for section 34–0507 including unit #129, November 1995.

APPENDIX D. FWD SN #129, APRIL 15, 1997–MAY 21, 1997

This sensor position error was recently identified using an automated screening version of SLIC, and reported in Feedback Report RNS–2M (see appendix A). This relatively short-lived misreporting of the actual position of d7 was not detected during the previous work done that resulted in Feedback Report RNS–2.

The automated version of SLIC used a model that was specifically chosen to predict the position of sensor 7 with a close to zero overall bias and the best possible precision (see appendix B). The first graph shown in this appendix (figure 16) is a plot of all the SN #129 d7 sensor position predictions during 1997 and 1998 for lane 1, drop height 4 FWD tests.

In figure 16, it can be seen that the average prediction for this 2-year period was around 152.4 cm (60 inches), as expected. The predictions are somewhat scattered, mainly due to the relatively large distance between d6 and d7. However, during the period of time in question (April 15, 1997–May 21, 1997), the position of d7 is clearly around 121.9 cm (48 inches) (average SLIC prediction for all flagged test dates = 121.9 cm (48 inches)), where in fact an empty sensor holder was usually positioned.

In figure 17, it can be seen clearly that the SN #129 predicted positions for sensor 7 in the spring of 1997 are outliers relative to the predicted positions for sensor 7 when other (correctly configured) FWDs are used. For the five test sections shown (from two different FWDs), the average predicted position of d7 was 154.2 cm (60.7 inches), while the average prediction for SN #129 during the period of time in question was 123.2 cm (48.5 inches).

In the two following graphs in this appendix, figures 18 and 19, respectively, the same results are shown graphically, with lines and data points labeled 5/13/1997 in figure 18 and 4/15/1997 in figure 19 showing the SLIC plot for d7 in both its actual position (121.9 cm (48 inches)) and the protocol but incorrect offset position (152.4 cm (60 inches)). The portions of the 5/13/1997 and 4/15/1997 lines that are parallel to the rest of the data are the correct plots, with d7 set at 121.9 cm (48 inches). Because of this information, it can be concluded with certainty that d7 was not positioned correctly at 152.4 cm (60 inches); rather, it was positioned at 121.9 cm (48 inches) (or very close to 121.9 cm (48 inches)) on FWD SN #129 between April 15, 1997 and May 21, 1997, inclusively. These dates correspond to the dates when lane 1 tests were conducted at drop height 4. This period of time may need to be extended somewhat if other tests were conducted along different lanes or at different drop heights. In any case, FWD tests conducted on or before March 25, 1997, and on or after June 3, 1997, clearly show d7 positioned at 152.4 cm (60 inches) (as per protocol).

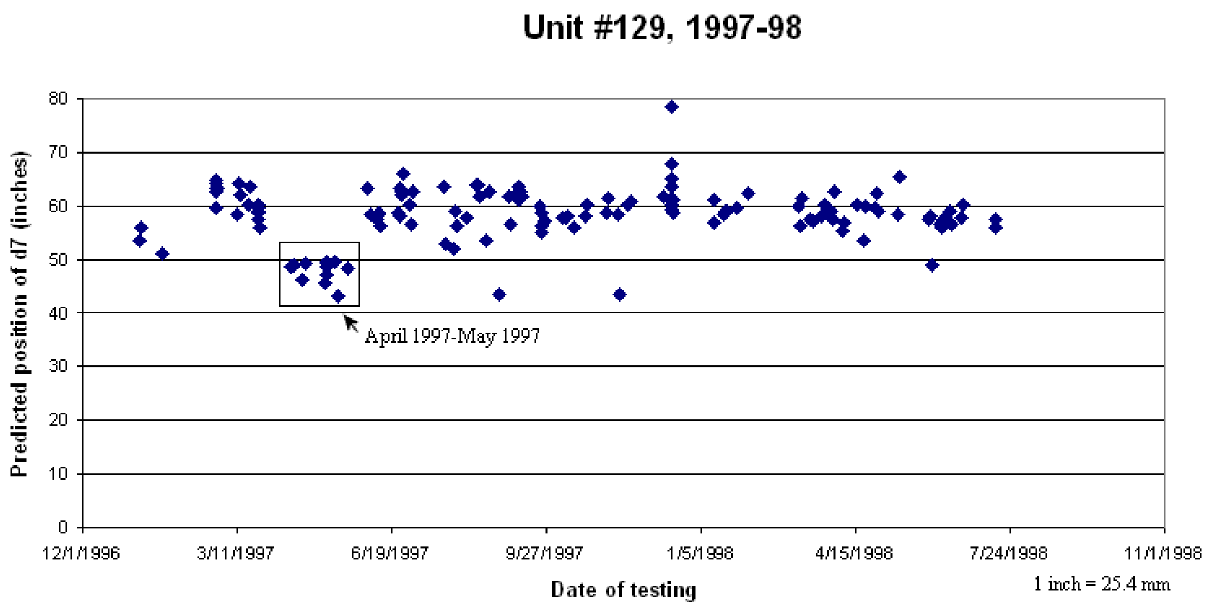


Figure 16. Graph. Predicted position of d7, unit #129, 1997–98.

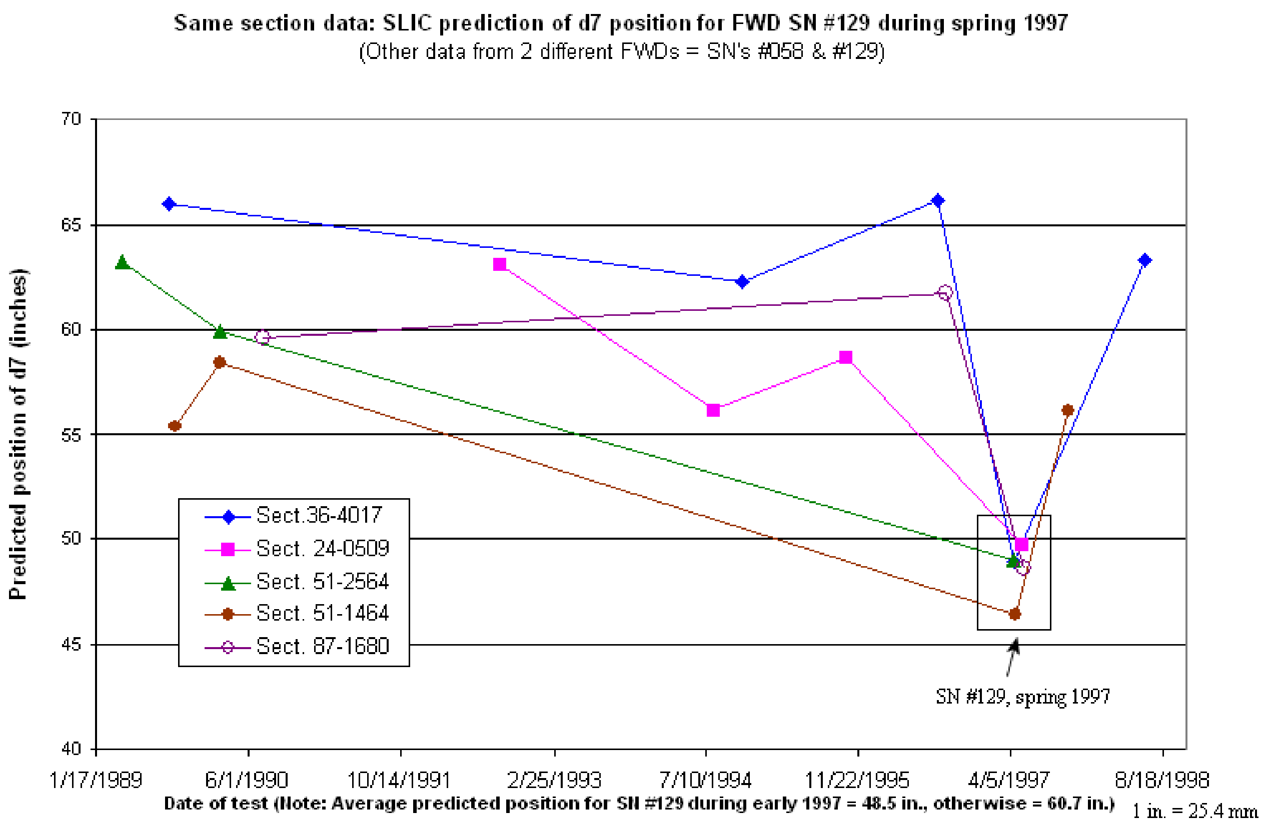


Figure 17. Graph. Same section data for d7 position, two different FWDs.

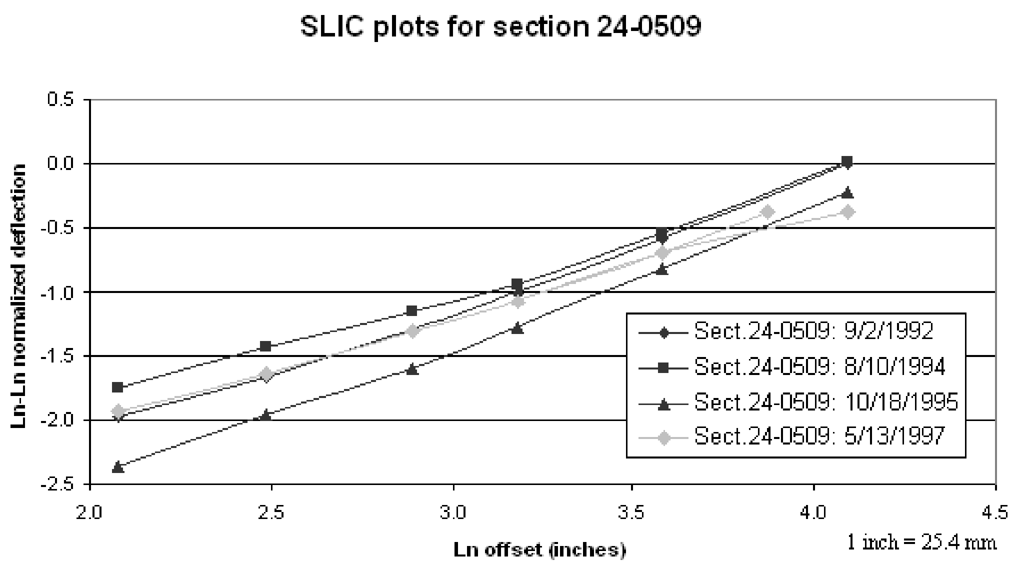


Figure 18. Graph. SLIC plots for section 24–0509 including unit #129, May 1997.

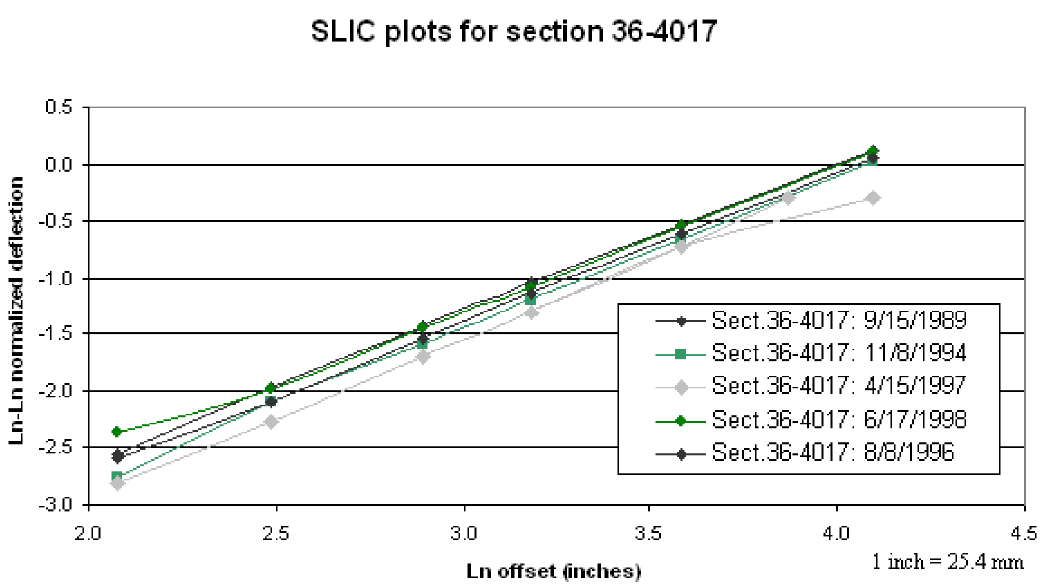


Figure 19. Graph. SLIC plots for section 36–4017 including unit #129, April 1997.

APPENDIX E. FWD SN #058, OCTOBER 15, 1997–MARCH 5, 1998

This sensor position error was recently identified using an automated screening version of SLIC and reported in Feedback Report RNS–2M (see appendix A). This relatively short-lived misreporting of the actual position of d7 was not detected during the previous work that resulted in Feedback Report RNS–2.

The automated version of SLIC used a model that was specifically chosen to predict the position of sensor 2 with a close to zero overall bias and the best possible precision (see Appendix B). The first graph shown in this appendix (figure 20) is a plot of all the SN #058 d2 sensor position predictions during 1997 and 1998 for all lane 1, drop height 4 FWD tests.

In figure 20, it can be seen that the average prediction for this 2-year period was around 20.3 cm (8 inches), as expected, albeit with some scatter. However, during the period of time in question (October 15, 1997–March 5, 1998), the average predicted position of d2 is clearly around 22.9 cm (9 inches) (average SLIC prediction for all flagged test dates = 23.4 cm (9.2 inches)).

In the figure that follows (figure 21), it can clearly be seen that the SN #058 predicted positions for sensor 2 in the fall and winter of 1997-98 are outliers relative to the predicted positions for sensor 2 when other correctly configured FWDs are used. For the four test sections shown (from two different FWDs), on average the predicted position of d2 was 20.6 cm (8.1 inches) while the average prediction for SN #058 during the same period of time in question was 22.9 cm (9 inches).

In the graph that follows (figure 22), the same result for a portion of the test dates is shown graphically, with the lines and data points labeled 11/13/1997 and 12/18/1997 showing the SLIC plot for d2 in both its protocol but incorrect (20.3 cm (8 inches)) and actual (22.9 cm (9 inches)) offset positions. The same test section was tested twice during the period of time in question, both times with FWD SN #058. The portions of the lines that are parallel to the rest of the data are the correct plots, with d2 set to 22.9 cm (9 inches).

Because of this information, it can be concluded with certainty that d2 was not positioned correctly at 20.3 cm (8 inches); rather, it was positioned at 22.9 cm (9 inches) (or very close to 22.9 cm (9 inches)) on FWD SN #058 between October 15, 1997 and March 5, 1998, inclusively. These dates correspond to the dates where lane 1 tests were conducted at drop height 4. This period of time may need to be extended slightly, if other tests were conducted along different lanes or at different drop heights. In any case, FWD tests conducted on or before September 9, 1997, and on or after April 6, 1998, clearly show d2 positioned at 20.3 cm (8 inches) (per protocol).

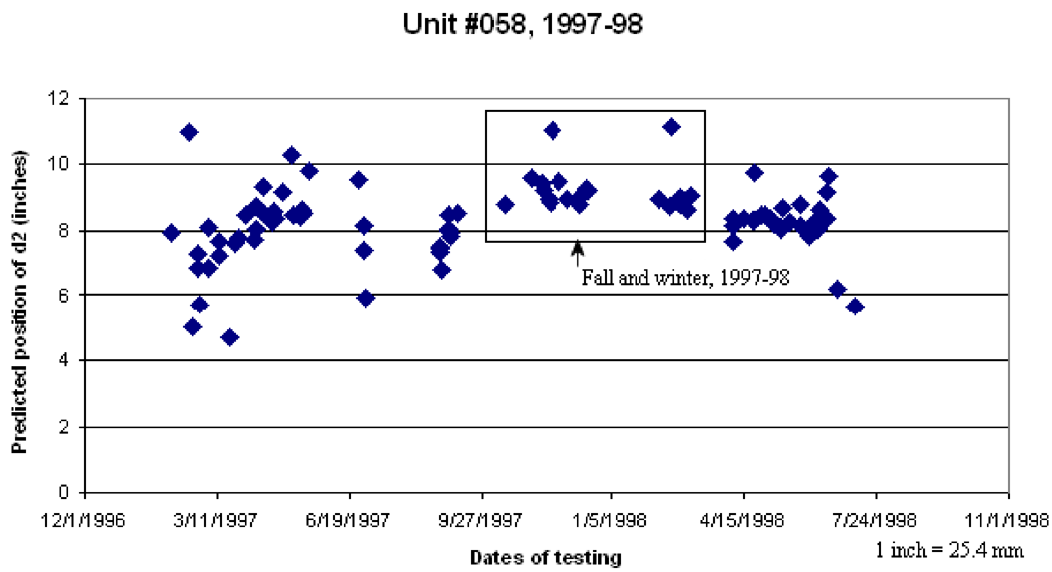


Figure 20. Graph. Predicted position of d2, unit #058, 1997–98.

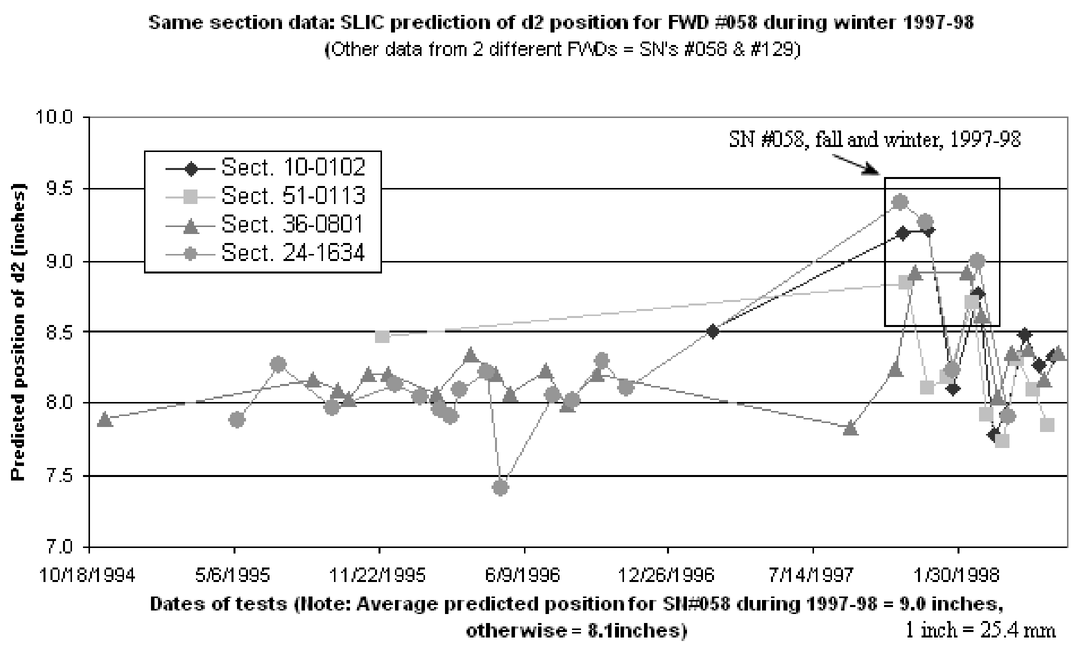


Figure 21. Graph. Same section data for d2 position, two different FWDs.

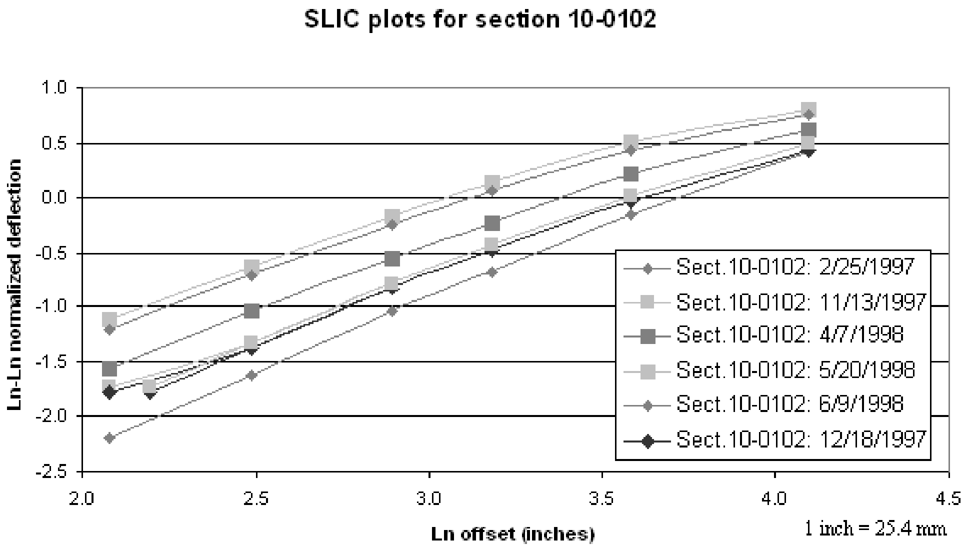


Figure 22. Graph. SLIC plots for section 10–0102 including unit #058, November–December 1997.

APPENDIX F. FWD SN #061, FEBRUARY 26, 1989–SEPTEMBER 8, 1989

These previously reported sensor position errors were located in the database and also identified and analyzed using an automated screening version of SLIC for the two regions in which they occurred (Regions 2 and 4). The SLIC screening versions used were tailored for predicting the positions of both sensors 2 and 7. Since several of the sensors were positioned somewhat differently from protocol, it was necessary to use the overall SLIC regression fits to verify the positioning errors found. The first graph shown in this appendix (see figure 23) is a plot of all the SN #061 values of R^2 for the d2 regression fits during all of 1989 and the first half of 1990, for lane 1, drop height 4 FWD tests. The second graph (figure 24) is the same plot of all the values of R^2 for the d7 regression fits over the same period of time.

In figures 23 and 24, it can be clearly seen that the average R^2 values during the period of time in question were generally between 0.980 and 0.990 (actual arithmetic average = 0.987). Generally, when the FWD sensors used in the regression are correctly placed, the regression produces a value of R^2 of 0.99**8** or better, on average. Clearly the R^2 values differed significantly during the period in question. Individual plots, such as those reproduced in figures 25 to 29 in this appendix, corroborate that the reported sensor configuration was nonprotocol.

It should be noted that other forensic work previously conducted revealed the following probable (metric) sensor positions: 0, 200, 300, 600, 750, 1200, and 1800 mm. Based on detailed analyses of the data, as shown in figures 25 to 29 in this appendix, it is just as likely that the sensor positions used were 0, 8, 12, 24, 30.5, 48, and 72 inches. In fact, all five section-specific plots depict these sensor positions. However, both possible sets of sensor positions plot almost equally well; thus, either set can be used with a high degree of confidence—and very little difference in terms of backcalculation results, since both are roughly the same (proportionally) in the two different units of measurement.

In figures 25 through 29, the results shown graphically utilize gray lines and data points for the dates that include the erroneous data, which were taken between February and September 1989. The gray lines and points show the plots for all sensors in both the sensors' actual (U.S. customary in these cases) and incorrect (protocol) offset positions. The portions of the gray lines that are parallel to the other data plots are the correct plots, with sensors d2 through d7 set to 0, 8, 12, 24, 30.5, 48, and 72 inches, respectively.

Because of this information, and the previous information supplied to FHWA, it can be concluded with certainty that the reported (protocol) sensor configuration was incorrect; rather, the correct configuration was either 0, 200, 300, 600, 750, 1200, and 1800 mm or 0, 8, 12, 24, 30.5, 48, and 72 inches on FWD SN #061 between February 26, 1989 and September 8, 1989. These dates correspond to the dates when lane 1 tests were conducted at drop height 4. This period of time may need to be extended slightly, if other tests were conducted along different lanes or at different drop heights. In any case, FWD tests conducted on or after September 11, 1989, indicate protocol sensor positions. FWD SN #061 was delivered to SHRP and driven to the Western Region sometime prior to February 26, 1989; all tests from the time of delivery through the beginning of September 1989 were conducted using the SLIC-determined sensor positions in lieu of the reported (protocol) positions.

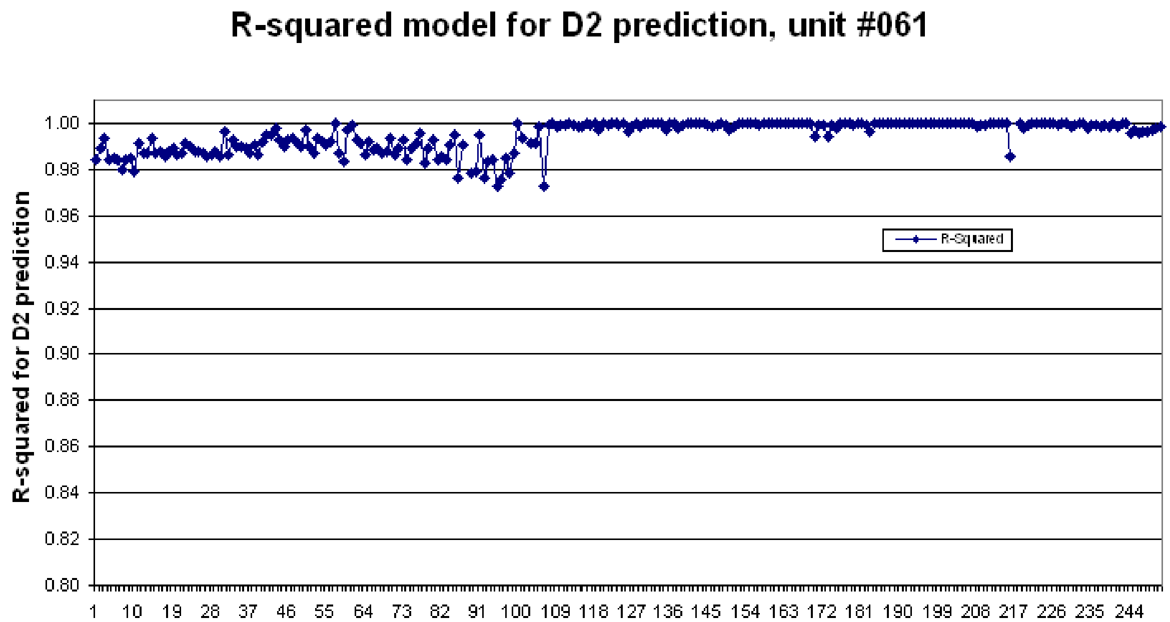


Figure 23. Graph. R^2 model for d2 prediction, unit #061, 1989–90.

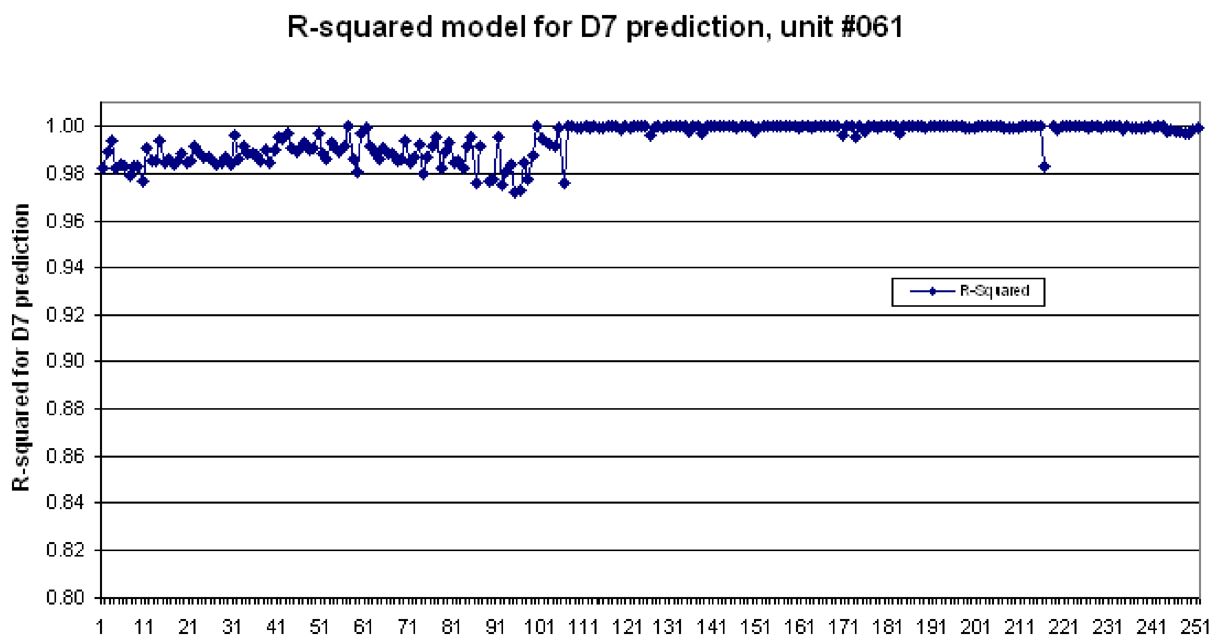


Figure 24. Graph. R2 model for d7 prediction, unit #061, 1989–90.

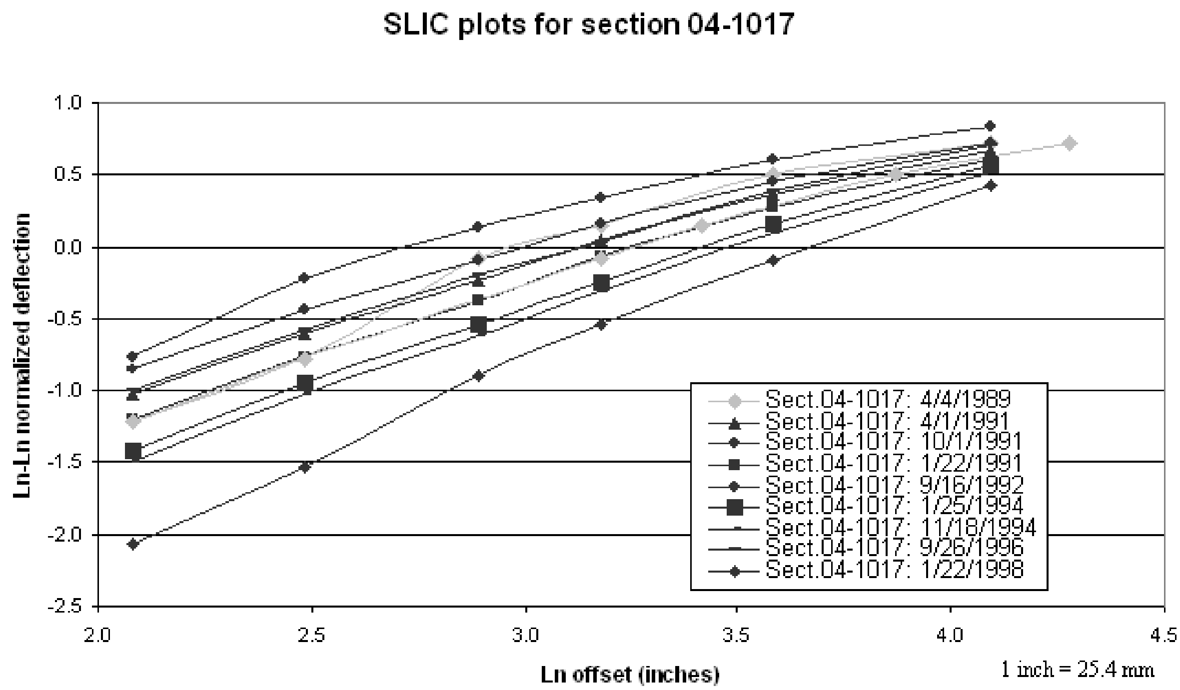


Figure 25. Graph. SLIC plots for section 04–1017 including unit #061, April 1989.

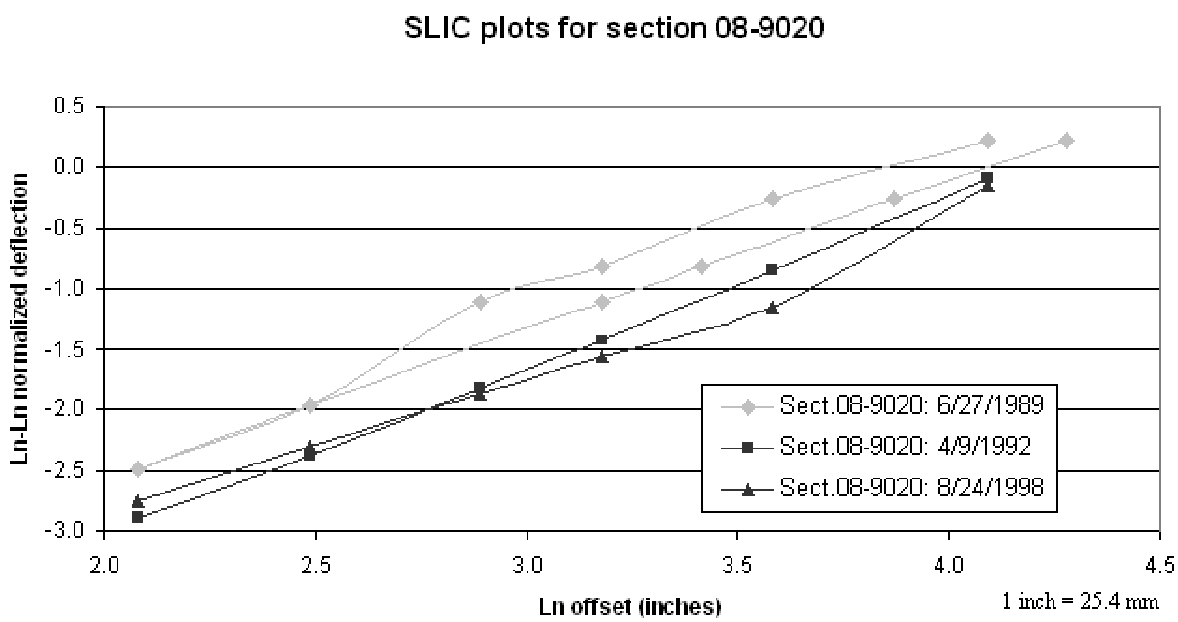


Figure 26. Graph. SLIC plots for section 08–9020 including unit #061, June 1989.

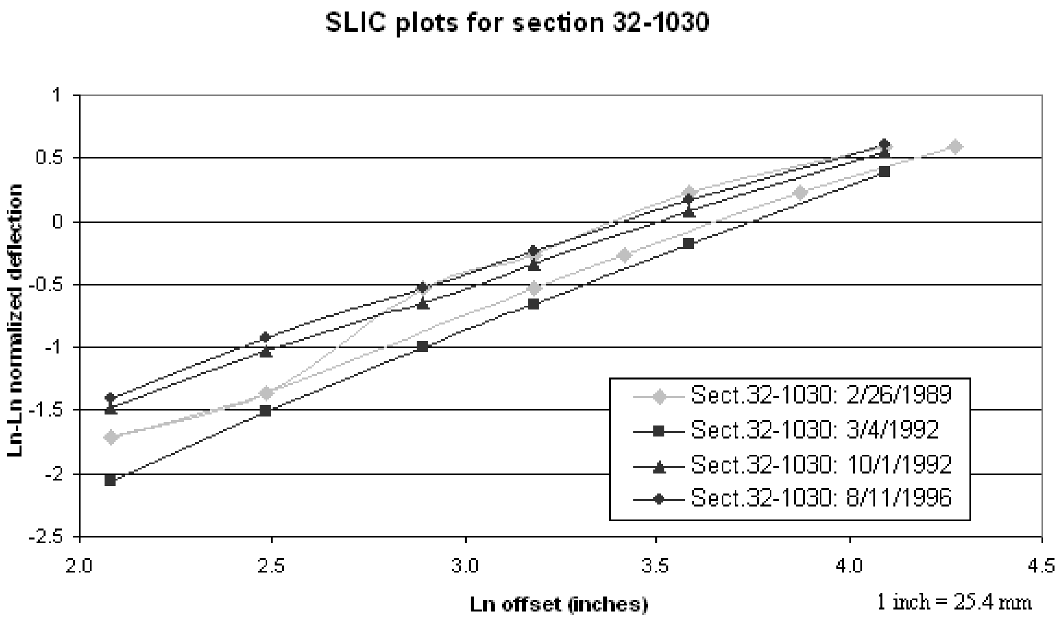


Figure 27. Graph. SLIC plots for section 32–1030 including unit #061, February 1989.

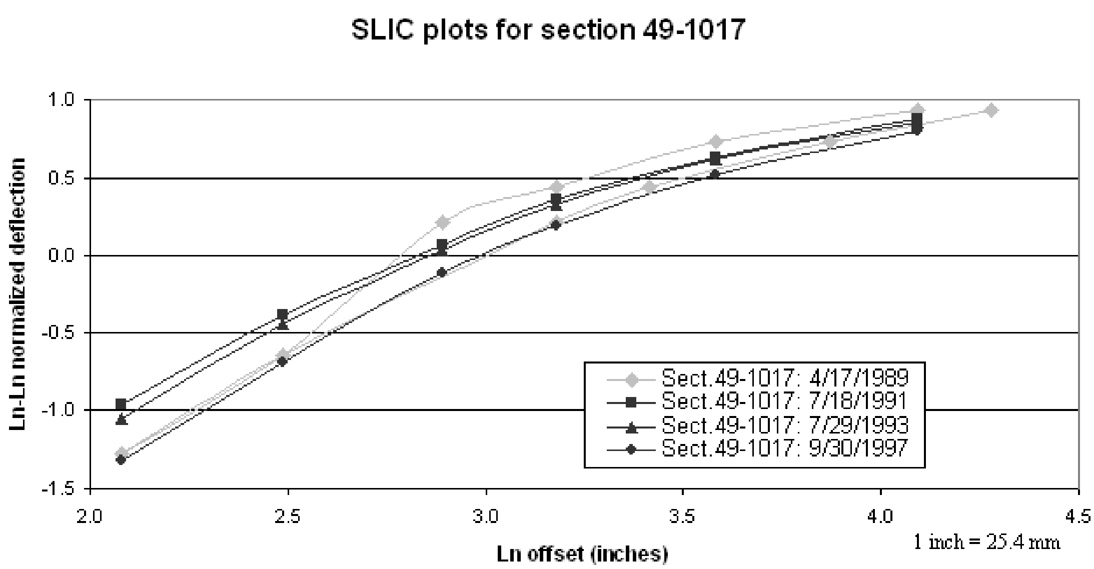


Figure 28. Graph. SLIC plots for section 49–1017 including unit #061, April 1989.

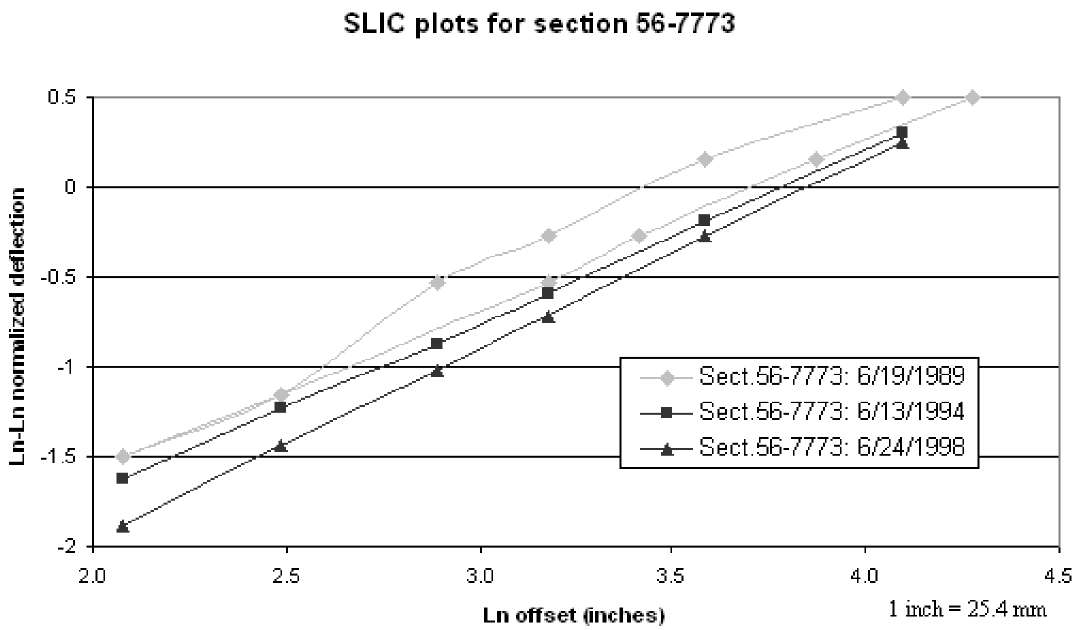


Figure 29. Graph. SLIC plots for section 56–7773 including unit #061, June 1989.

APPENDIX G. FWD SN #130, AUGUST 25, 1994–SEPTEMBER 7, 1994

This previously reported sensor position error was located in the database using an automated version of SLIC which employs a model that was specifically chosen to predict the position of sensor 7 with a close to zero overall bias and the best possible precision (see appendix B). With this method, after regressions are fit to the model 7 prediction based on the data from sensors 3 through 6, two plots for each FWD are created. One is a plot of the sequence of R^2 terms, and the other is the predicted position of sensor 7. The first graph shown in this appendix (figure 30) is a plot of all of the R^2 values for FWD SN #130, for the regression that best fits each test date using the data from sensors 3 through 6. The period of time was 1994 through the end of 1996, and the data are for lane 1, drop height 4 FWD tests. The second graph in this appendix (see figure 31) uses the same period of time and data to predict the position of sensor 7 for each test date.

In both figures 30 and 31, it can be seen that there is a serious anomaly starting at test sequence 50, which corresponds to August 25, 1994. The average R^2 value during the period of time in question was only 0.881, whereas when the FWD sensors used in the regression are correctly placed, the regression fits so well that the values of R^2 are generally 0.998 or better. Based on a detailed analysis of the data, for example as shown in the succeeding three figures in this appendix, it is clear that the sensor positions used were 0, 8, 12, 18, 36, 48, and 60 inches. All three section-specific plots depict these sensor positions, with d5 and d6 simply shifted 12 inches into the wrong sensor holders, leaving the 24-inch sensor holder inadvertently empty.

In figures 32, 33, and 34, the gray lines and data points are plots of both actual and erroneous data for d5 and d6 for the particular date. The gray lines that are parallel to the rest of the data are the correct plots, with d5 and d6 set to 61 cm (24 inches) and 91.4 cm (36 inches), respectively.

Because of this information, and the previous information supplied to FHWA, it can be concluded with certainty that d5 and d6 were not positioned correctly, at 61 cm (24 inches) and 91.4 cm (36 inches) respectively; rather, they were positioned at 91.4 cm (36 inches) and 121.9 cm (48 inches) (or very close to these positions) respectively, on FWD SN #130 between August 25, 1994, and September 7, 1994. These dates correspond to the dates when the data generated included lane 1 tests from drop height 4. This period of time may need to be extended slightly, if other tests were conducted along different lanes or at different drop heights. In any case, FWD tests conducted on or before August 22, 1994 and on or after September 8, 1994, clearly show that d5 and d6 were correctly positioned at 61 cm (24 inches) and 91.4 cm (36 inches) (as per protocol), respectively.

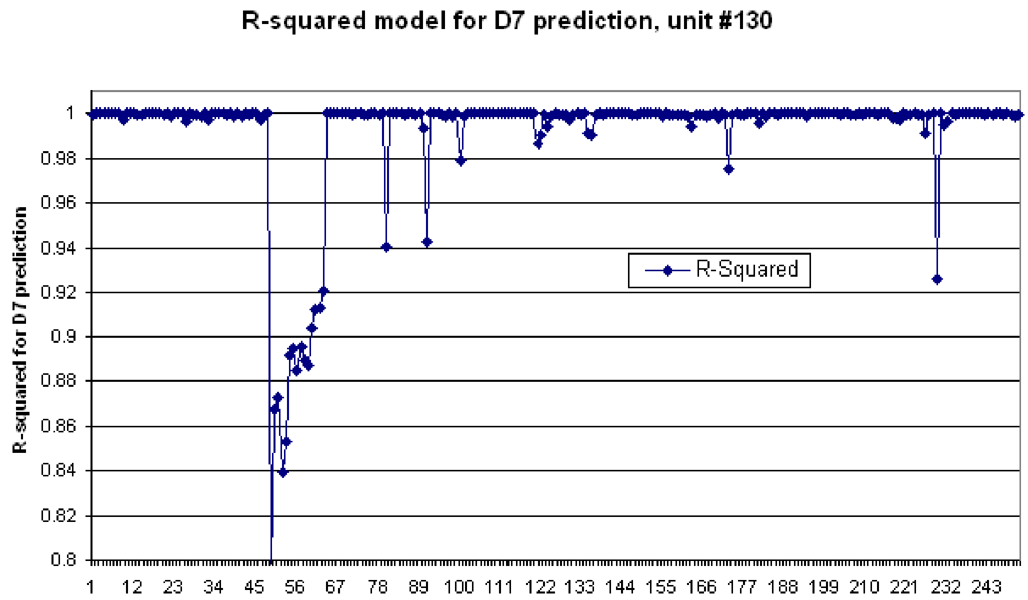


Figure 30. Graph. R^2 model for d7 prediction, unit #130, 1994–96.

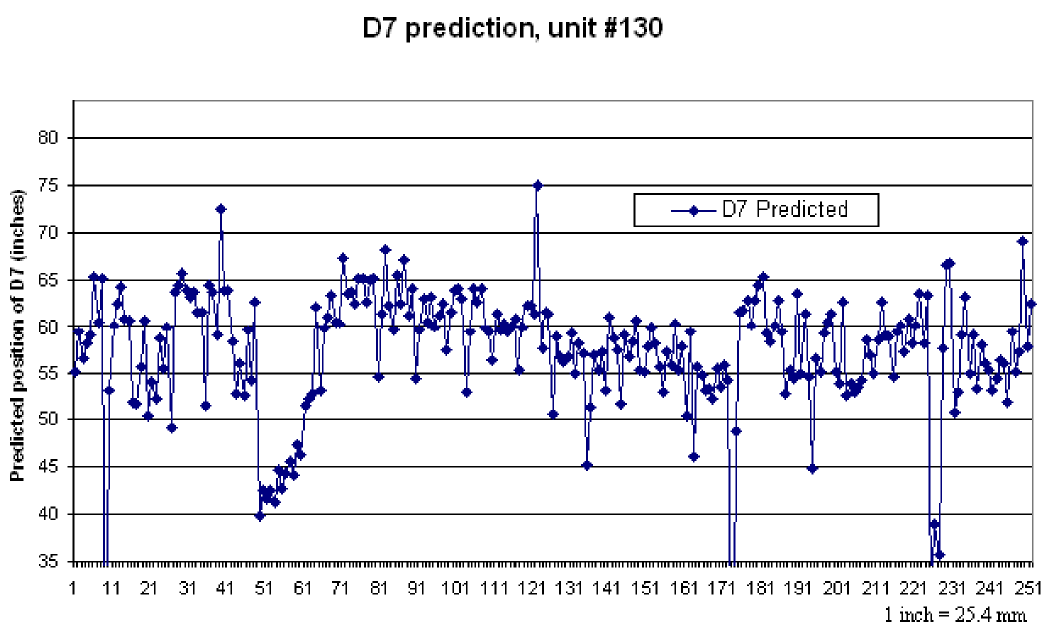


Figure 31. Graph. Predicted position of d7, unit #130, 1994–96.

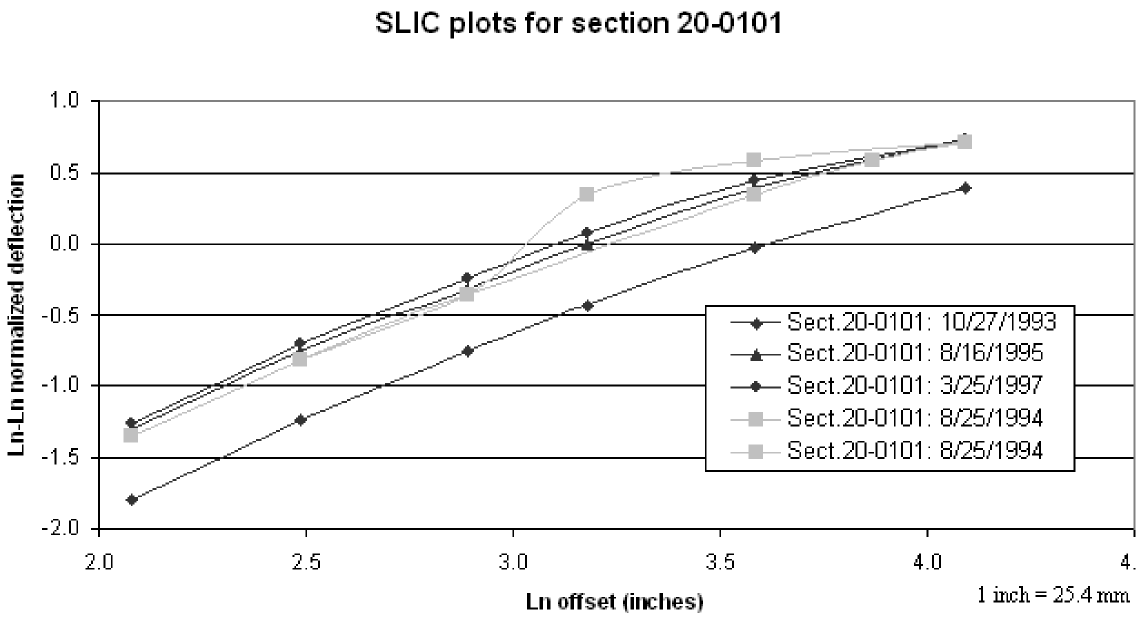


Figure 32. Graph. SLIC plots for section 20–0101 including unit #130, August 1994.

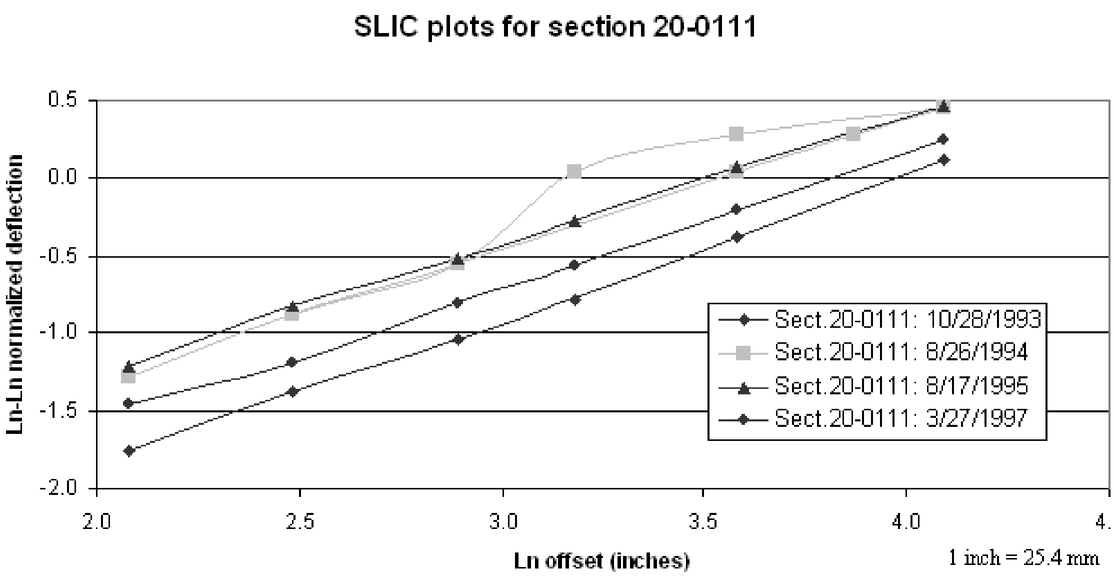


Figure 33. Graph. SLIC plots for section 20–0111 including unit #130, August 1994.

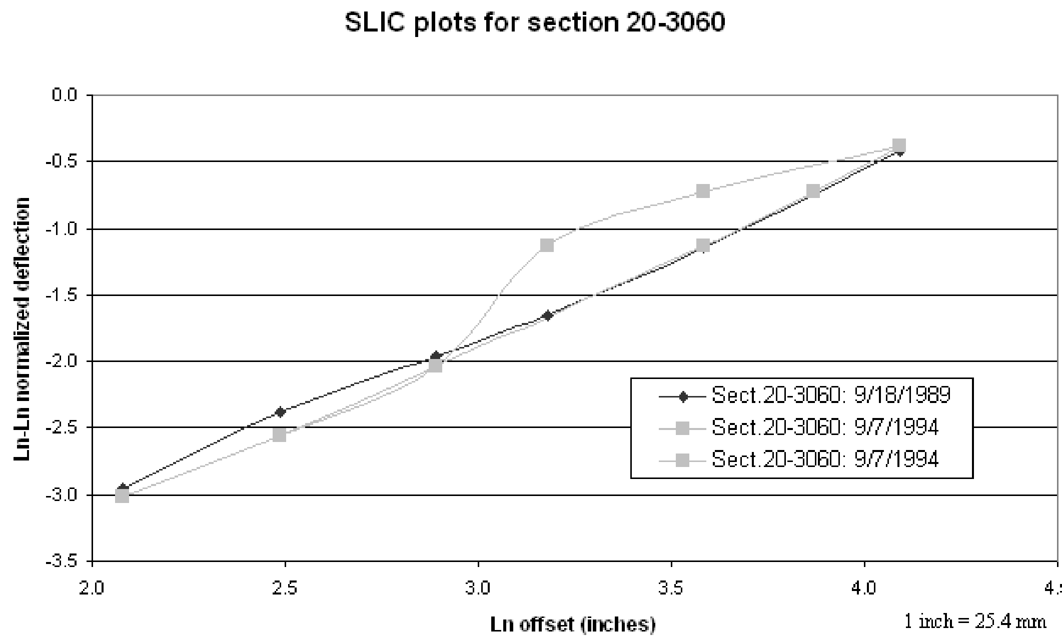


Figure 34. Graph. SLIC plots for section 20–3060 including unit #061, September 1994.

APPENDIX H. FWD SN #075, JANUARY 17, 1990–JANUARY 22, 1990

These previously reported sensor position errors were located in the database and also identified and analyzed using an automated screening version of SLIC. The SLIC screening versions used were tailored for predicting the position of sensors 2 and 7. Since in this case three of the sensors were positioned differently from protocol, the overall SLIC regression fit was mainly used to verify the positioning errors found. The first graph shown in this appendix (figure 35) is a plot of all the SN #075 values of R^2 for the d2 and d7 regression fits from 1990 through 1997, for lane 1, drop height 4 FWD tests.

In figure 35, it can be seen that there is a serious anomaly starting when SN #075 was first used, presumably on January 17, 1990. The average R^2 value during the period of time in question was only 0.963, whereas when the FWD sensors used in the regression are correctly placed, the regression fit is generally 0.998 or better. Clearly the R^2 values change dramatically for the better after the period of time in question. Individual plots like those shown in the succeeding two graphs corroborate that the reported protocol configuration was incorrect.

Based on a detailed analysis of the data, for example as shown in figures 36 and 37, it is clear that the sensor positions used were 0, 8, 12, 18, 30, 42, and 66 inches. Both section-specific plots depict these sensor positions, with d5, d6, and d7 shifted 6 inches farther from the plate, probably due to one minor and inadvertent error in the distance measurement between sensors 4 and 5. Alternatively, the distance to these sensors may have been inadvertently measured from the edge of the loading plate rather than from the center of the plate where sensor 1 is located.

In figures 36 and 37, the gray lines and data points are plots of both actual and erroneous data for d5, d6, and d7 for the particular date. The gray lines that are parallel to the rest of the data are the correct plots, with d5, d6, and d7 set to 76.2 cm (30 inches), 106.7 cm (42 inches) and 167.6 cm (66 inches), respectively.

Because of this information, and the previous information supplied to FHWA, it can be concluded with certainty that d5, d6, and d7 were not positioned in their protocol positions; rather, they were positioned at 76.2 cm (30 inches), 106.7 cm (42 inches) and 167.6 cm (66 inches), respectively (or very close to these positions), on FWD SN #075 between January 17, 1990, and January 22, 1990. These dates correspond to the dates when lane 1 tests were conducted at drop height 4. This period of time may need to be extended slightly if other tests were conducted along different lanes or at different drop heights. In any case, FWD tests conducted on or after February 9, 1990, indicate protocol sensor positions. FWD SN #075 was first used for lane 1, drop height 4 tests on January 17, 1990; it is also possible that it was used prior to this date, if different lanes or drop heights were used for LTPP testing (excluding the lane 1, drop height 4 test sequence).

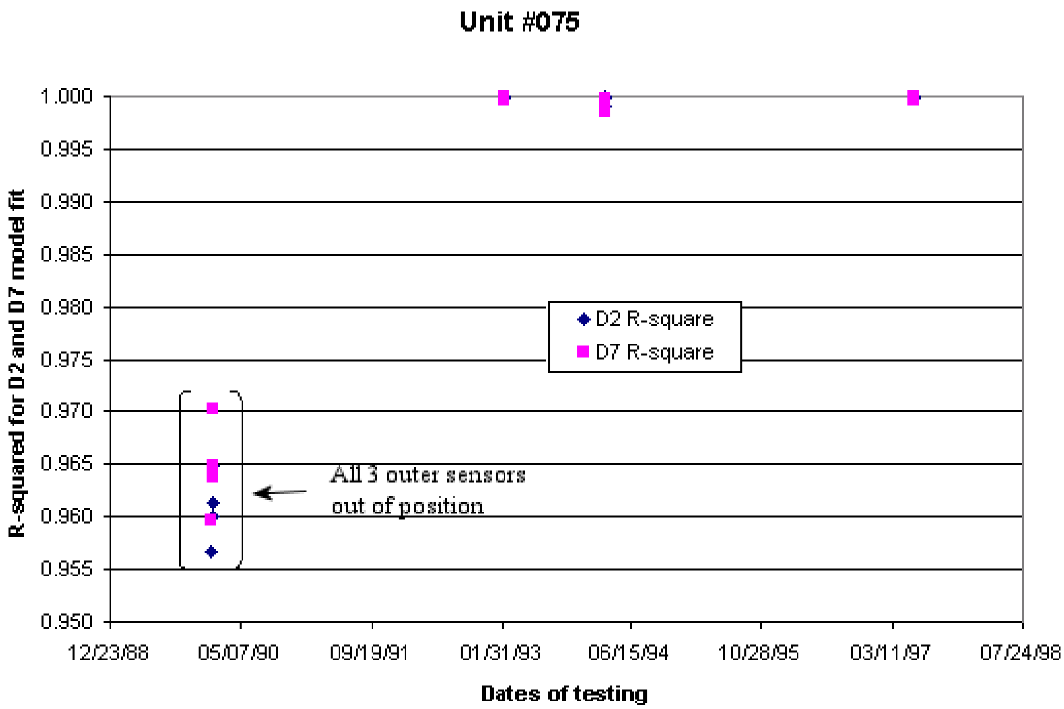


Figure 35. Graph. R^2 model for d2 and d7 predictions, unit #075, 1990–97.

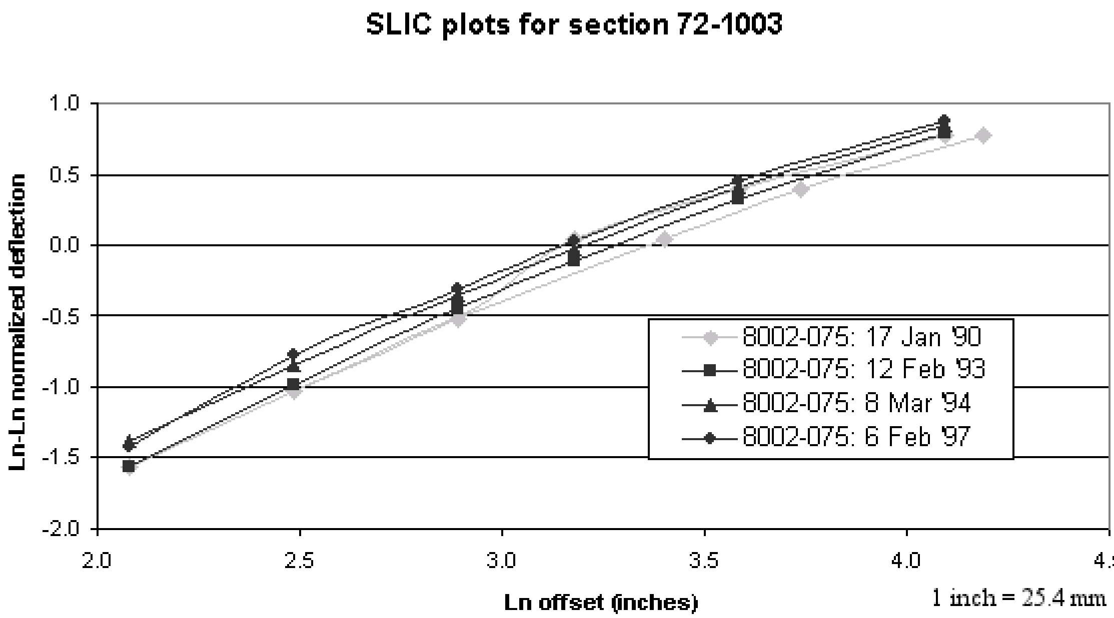


Figure 36. Graph. SLIC plots for section 72–1003 including unit #075, January 1990.

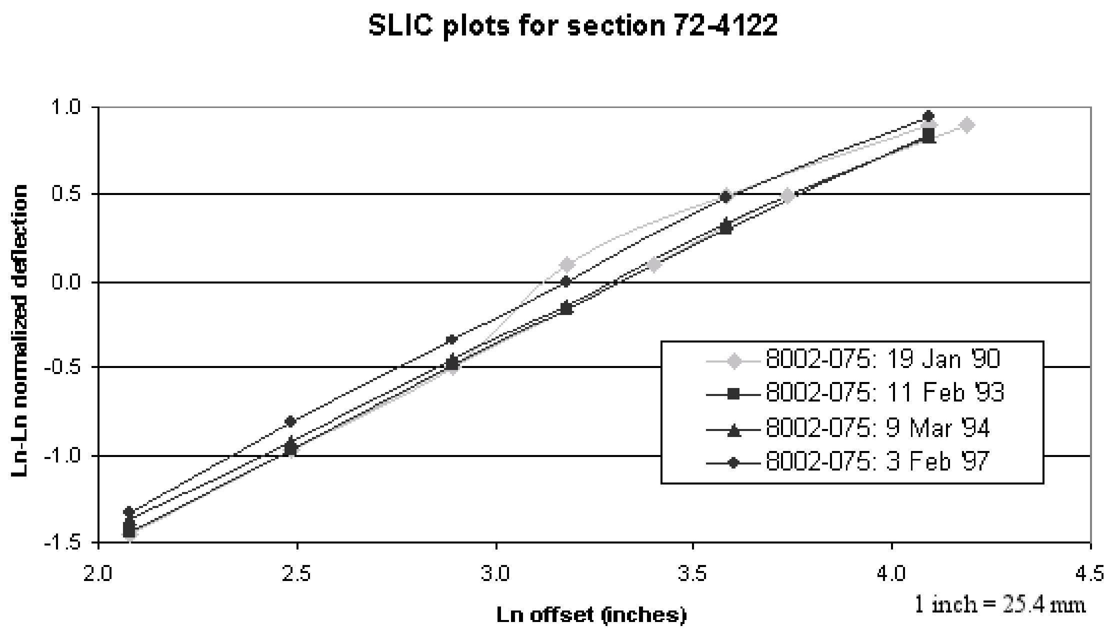


Figure 37. Graph. SLIC plots for section 72–4122 including unit #075, January 1990.

APPENDIX I. FWD SN #132, JULY 29, 1996–OCTOBER 25, 1996

This previously reported sensor position error was located in the database using an automated screening version of SLIC. This screening version is tailored for sensor 7 (among others), with a close to zero overall bias and the best possible precision (see appendix B). The first three graphs shown in this appendix (see figures 38, 39, and 40) are plots of all the SN #132 d7 sensor position predictions during 1995 to 1997 for lane 1, drop height 4 FWD tests. In these graphs, it can be seen that the average prediction for this 3-year period, excepting the data for the dates in question, was around 152.4 cm (60 inches), as expected. However, during the period of time in question (July 29, 1996 to October 25, 1996), the average predicted position of d7 is clearly around 121.9 cm (48 inches) (average SLIC prediction for all flagged test dates = 122.2 cm (48.1 inches)). In fact, an empty sensor holder is generally positioned at 121.9 cm (48 inches).

In the fourth figure in this appendix, figure 41, it clearly can be seen that the SN #132 predicted positions for sensor 7 in mid-1996 are outliers relative to the predicted positions for sensor 7 when other (correctly configured) FWDs are used. For the seven test sections shown (from three different FWDs), on average the predicted position of d7 was 154.9 cm (61 inches) while the same prediction for SN #132 during the period of time in question was 121.4 cm (47.8 inches).

In the two figures that follow, figures 42 and 43, the same results are shown graphically, with the gray lines and data points showing the SLIC plots for d7 in both its actual (121.9 cm (48 inches)) and protocol but incorrect (152.4 cm (60 inches)) offset positions. The gray lines that are parallel to the rest of the lines are the correct plots, with d7 set to 121.9 cm (48 inches).

Because of this information, and the previous information supplied to FHWA, it can be concluded with certainty that d7 was positioned at 121.9 cm (48 inches) (or very close to 121.9 cm (48 inches)) on FWD SN #132 between July 29, 1996 and October 25, 1996. These dates correspond to the dates when lane 1 tests were conducted at drop height 4. This period of time may need to be extended slightly, if other tests were conducted along different lanes or at different drop heights. In any case, FWD tests conducted on or before June 6, 1996, and on or after November 5, 1996, clearly show d7 positioned at 152.4 cm (60 inches) (per protocol).

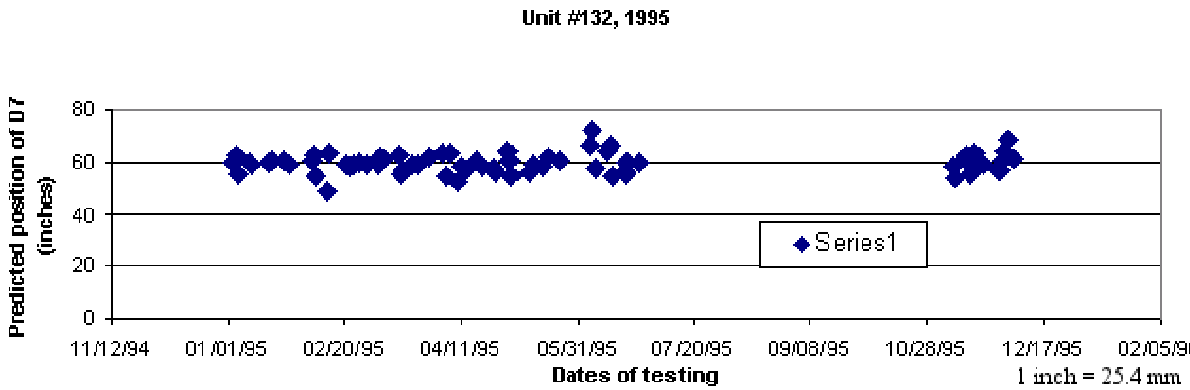


Figure 38. Graph. Predicted position of d7, unit #132, 1995.

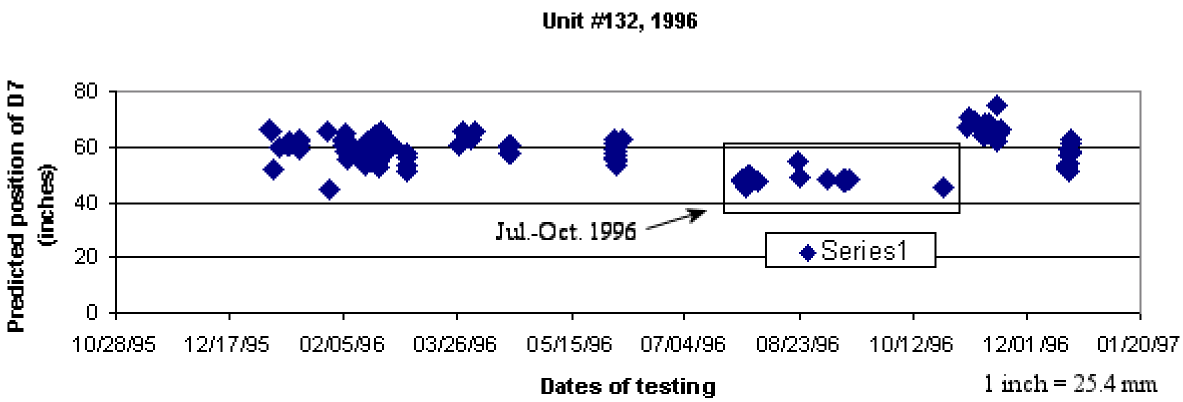


Figure 39. Graph. Predicted position of d7, unit #132, 1996.

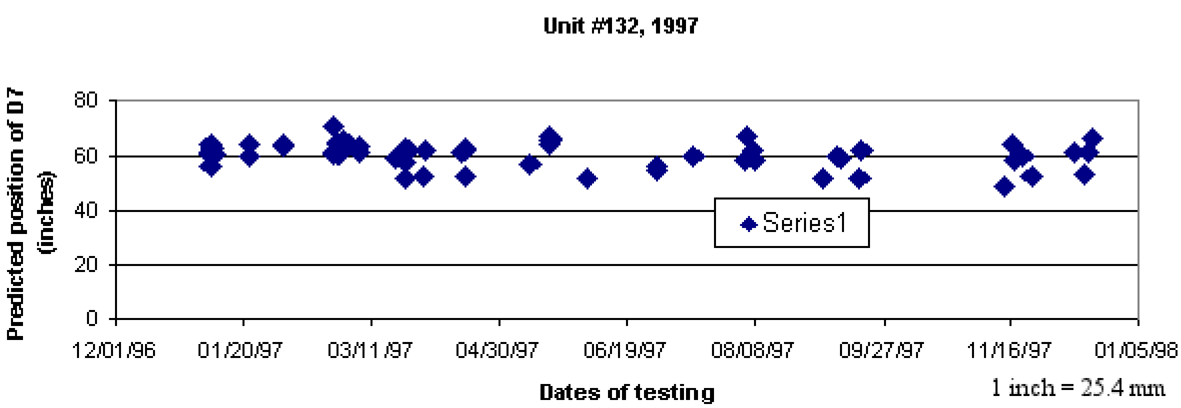


Figure 40. Graph. Predicted position of d7, unit #132, 1997.

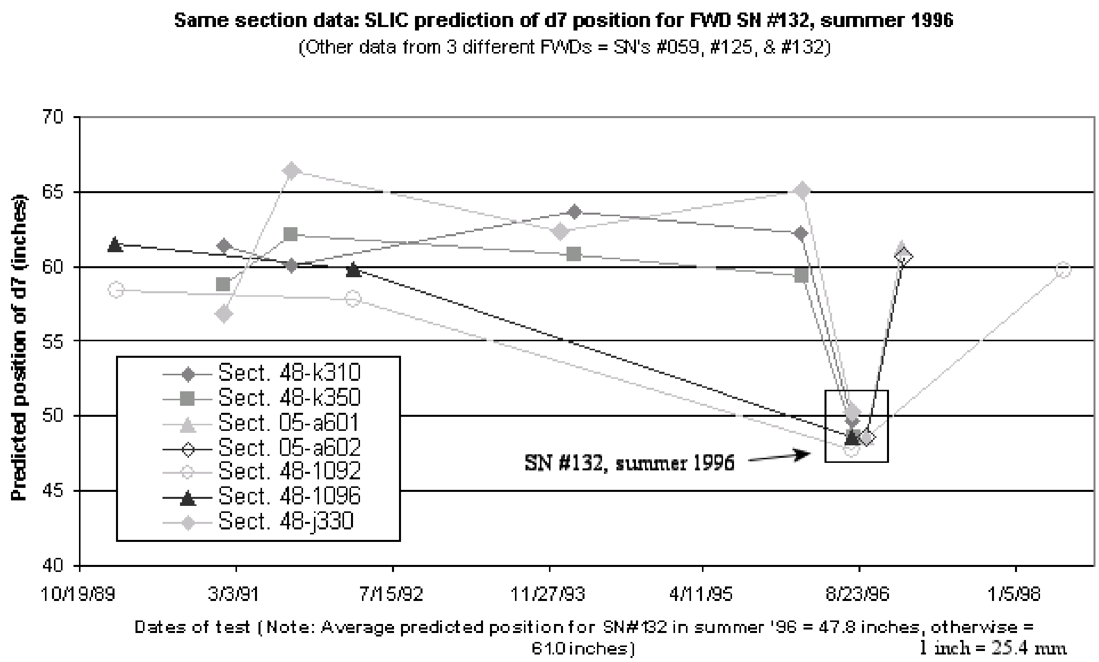


Figure 41. Graph. Same section data for d7 position, three different FWDs.

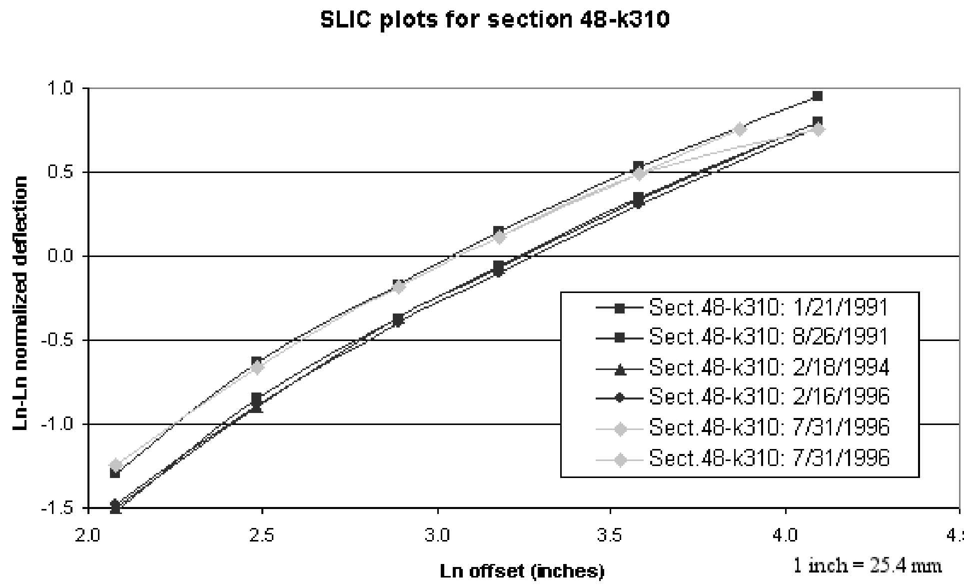


Figure 42. Graph. SLIC plots for section 48–k310 including unit #132, July 1996.

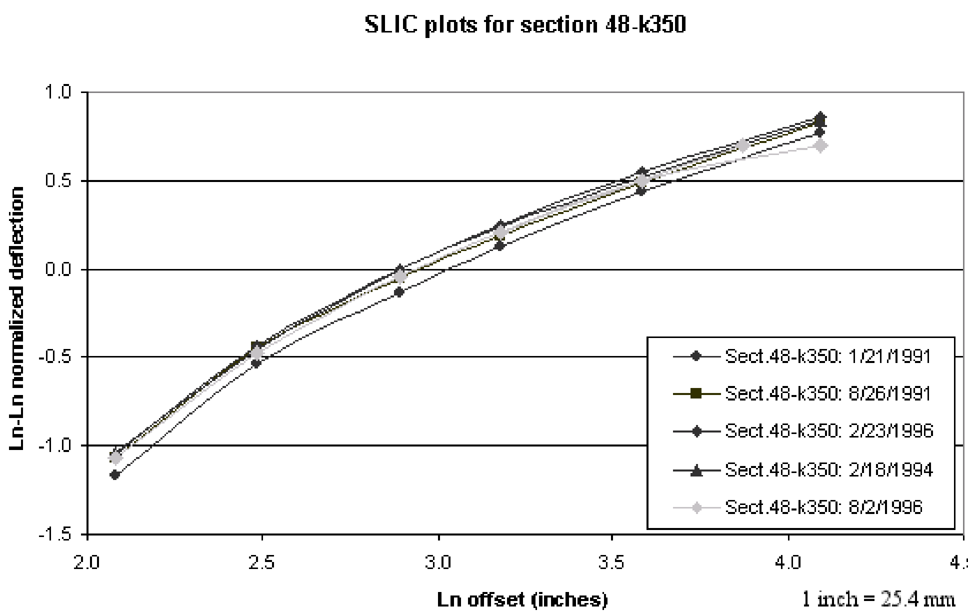


Figure 43. Graph. SLIC plots for section 48–k350 including unit #132, August 1996.

APPENDIX J. FWD SN #061, JULY 17, 1995–OCTOBER 31, 1995

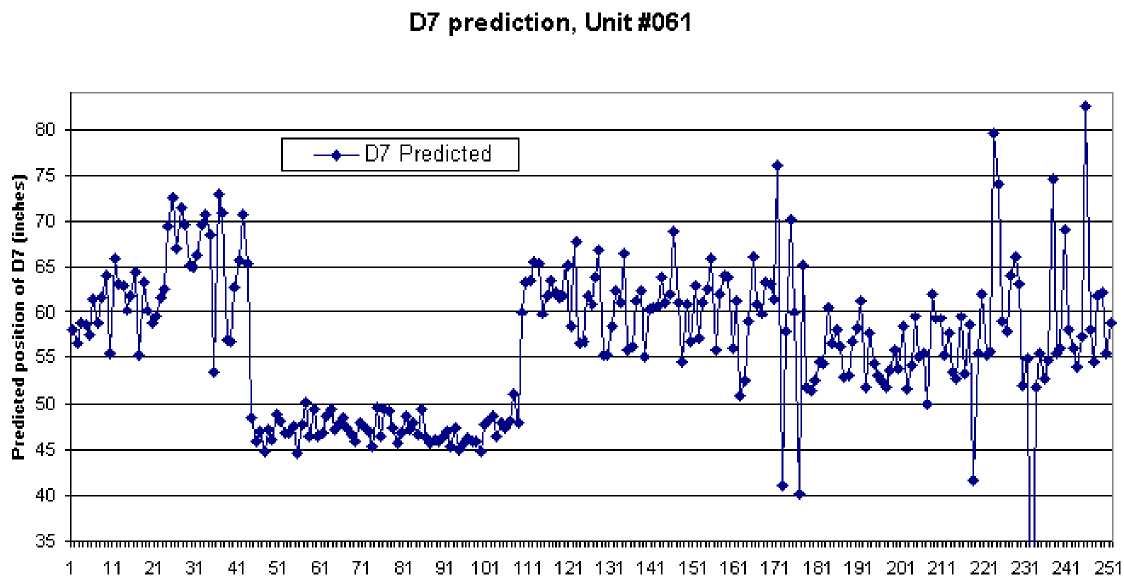
This previously reported sensor position error was located in the database using an automated screening version of SLIC. This screening version is tailored for sensor 7 (among others), with a close to zero overall bias and the best possible precision (see appendix B). The first graph shown in this appendix (figure 44) is a plot of all the SN #061 values for the d7 sensor position predictions from November 1994 through March 1997, for all lane 1, drop height 4 FWD tests.

In figure 44 it can be seen that the average prediction for this 2-year plus period, excepting the data for the dates in question, was around 152.4 cm (60 inches), as expected. The predictions are somewhat scattered, mainly due to the relatively large distance of d7 from the loading plate when in its protocol position (152.4 cm (60 inches)). However, during the period of time in question (July 17, 1995 to October 31, 1995), the average predicted position of d7 is clearly around 121.9 cm (48 inches) (average SLIC prediction for all flagged test dates = 119.9 cm (47.2 inches)). In fact, an empty Dynatest sensor holder should have been positioned at 121.9 cm (48 inches) during this period of time.

In the second figure in this appendix (see figure 45), it can clearly be seen that the SN #061 predicted positions for sensor 7 for the dates in question are outliers relative to the predicted positions for sensor 7 when correctly configured FWDs are used. Once again, the prediction for the position of sensor 7 is close to 121.9 cm (48 inches). For the seven test sections shown (from three different FWDs), on average the predicted position of d7 was 148.3 cm (58.4 inches), while the same prediction for SN #061 during the period of time in question was 118.4 cm (46.6 inches).

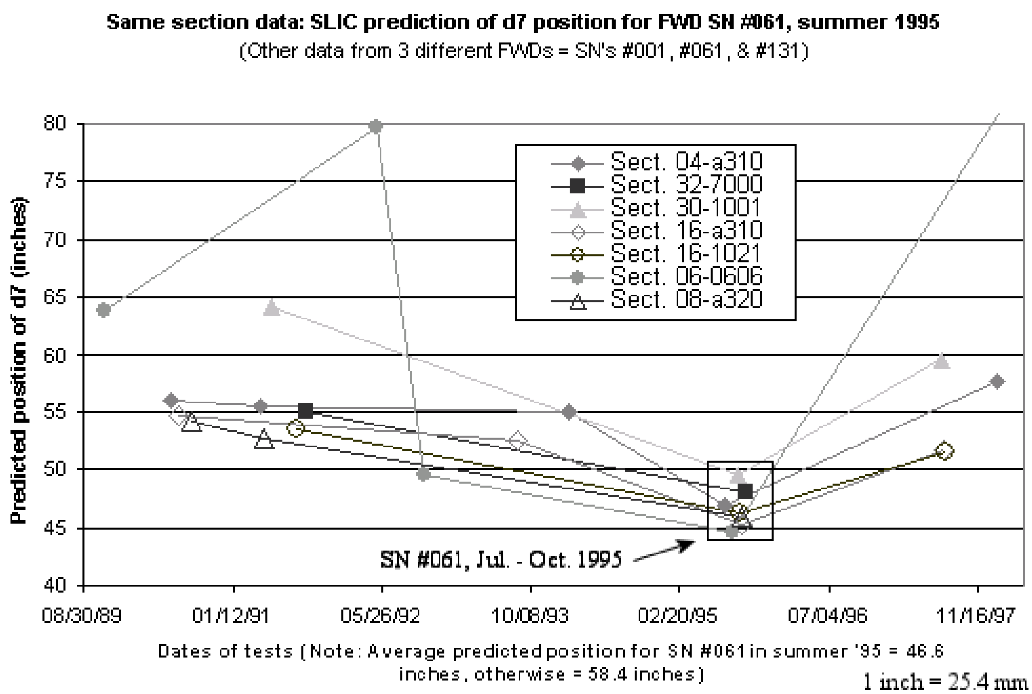
In the two following figures in this appendix, figures 46 and 47, the same results are shown graphically, with the light gray lines and data points showing the SLIC plots for d7 in both its actual (121.9 cm (48 inches)) and incorrect (152.4 cm (60 inches)) offset positions. The portions of the light gray lines that are parallel to the rest of the lines are the correct plots, with d7 set to 121.9 cm (48 inches). In one of these two cases (figure 47), it can also be seen that the data includes another sensor spacing error for SN #061, namely the 1989 error covered in appendix F. In this case, the SLIC-determined metric sensor positions have been used, which, when transformed, correctly plots the data for section 32–7000 on a parallel line, for FWD tests conducted on May 5, 1989 (in this case with *black* lines and data points).

Because of this information, and the previous information supplied to FHWA, it can be concluded with certainty that d7 was *not* positioned correctly at 152.4 cm (60 inches); rather, it was positioned at 121.9 cm (48 inches) (or very close to 121.9 cm (48 inches)) on FWD SN #061 between July 17, 1995, and October 31, 1995. These dates correspond to the dates when lane 1 tests were conducted at drop height 4. This period of time may need to be extended slightly, if other tests were conducted along different lanes or at different drop heights. In any case, FWD tests conducted on or before March 31, 1995, and on or after November 14, 1995, clearly show d7 positioned at 152.4 cm (60 inches) (per protocol).



1 inch = 25.4 mm

Figure 44. Graph. Predicted position of d7, unit #061, 1994–97.



1 inch = 25.4 mm

Figure 45. Graph. Same section data for d7 position, three different FWDs.

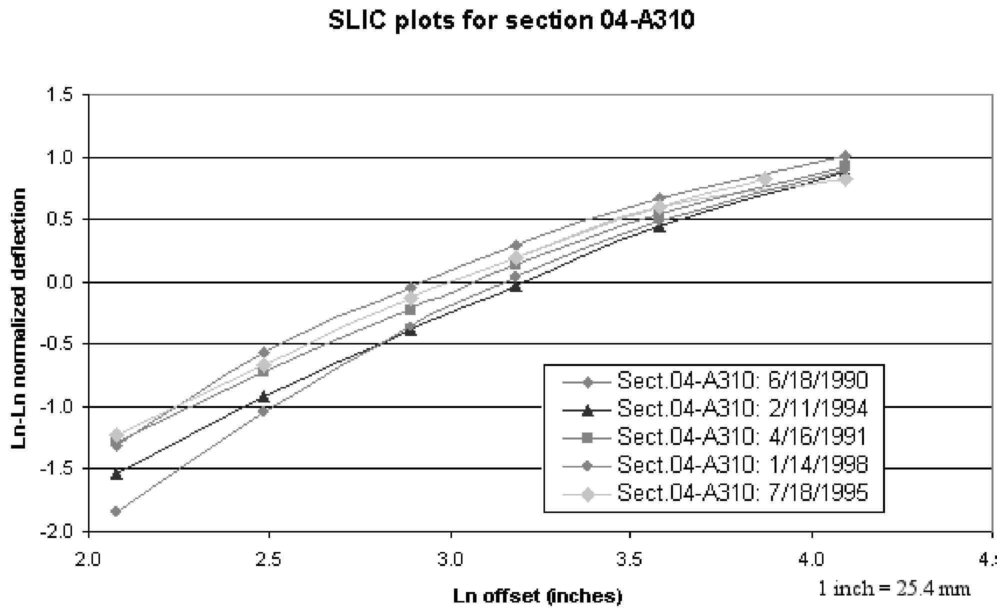


Figure 46. Graph. SLIC plots for section 04–A310 including unit #061, July 1995.

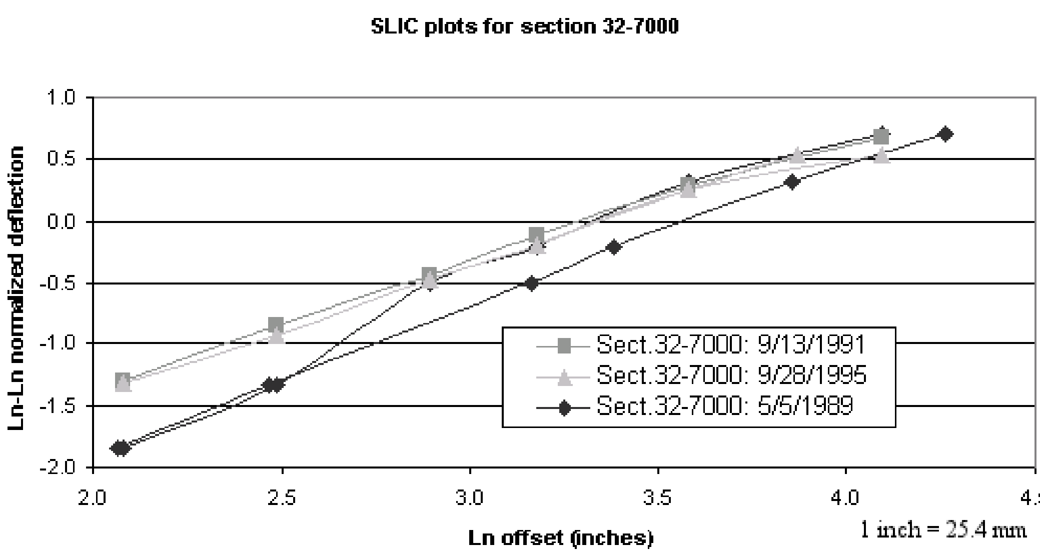


Figure 47. Graph. SLIC plots for section 32–7000 including unit #061, September 1995.

APPENDIX K. FWD SN #131, MAY 24, 1994–APRIL 30, 1996

This previously reported (and physically measured) d7 sensor position error was located in the database and also identified and analyzed using an automated screening version of SLIC. This screening version is tailored for sensor 7 (among others), with a close to zero overall bias and the best possible precision (see appendix B). The first graph shown in this appendix (figure 48) is a plot of all the SN #131 d7 sensor position predictions from May 1994 through the middle of March 1997, for all lane 1, drop height 4 FWD tests.

In figure 48, it can be seen that the average prediction subsequent to the initial time period where d7 was positioned incorrectly was around 152.4 cm (60 inches), with some scatter due to the relatively large distance between d6 and d7. However, during the period of time in question (May 24, 1994 to April 30, 1996), the average predicted position of d7 is approximately 121.9 cm (48 inches) (average SLIC prediction for all flagged test dates = 120.7 cm (47.5 inches)). In fact, an empty Dynatest sensor holder was originally positioned at 121.9 cm (48 inches) when this unit was delivered.

In figure 49, it can be seen that when the same LTPP test sections are plotted as a function of the predicted position of d7, SN #131 for the period May 1994 to April 1996 is an outlier. As shown elsewhere, the average prediction for the d7 sensor is around 121.9 cm (48 inches), which is precisely where it was found in 1996 when a physical measurement was made on this unit of the d7 offset. For the six test sections shown (from four different FWDs), on average the predicted position of d7 was 155.7 cm (61.3 inches), while the same prediction for SN #131 during the period of time in question was 121.9 cm (48 inches).

In the two following graphs in this appendix, figures 50 and 51, the same results are shown graphically, with the light gray lines and data points showing the SLIC plot for d7 in both its actual (121.9 cm (48 inches)) and protocol but incorrect (152.4 cm (60 inches)) offset position. The light gray lines that are parallel to the rest of the data are the correct plots, with d7 set to 121.9 cm (48 inches). In the first of these two cases (see figure 50), it can also be seen that the data includes another sensor spacing error for SN #061, namely the 1989 error covered in appendix F. In this case, the SLIC-determined metric sensor positions have been used, which, when transformed, also plot the data for section 08–6002 on a parallel line, for FWD tests conducted on July 13, 1989 (black lines and data points). In the second case (see figure 51), it can be seen as well that the data includes yet another sensor spacing error for SN #061, namely the 1995 error covered in appendix J (also a d7 shift from the 152.4 cm (60 inches) protocol position to 121.9 cm (48 inches)—see the black lines and data points). The medium gray line and data points was from yet another d7 position uncertainty for SN #061; however, in this case the likelihood of a 152.4 cm (60 inches) protocol position is about the same as the SLIC-determined position, approximately 137.2 cm (54 inches).

Because of this information, and the previous information supplied to FHWA, it can be concluded with certainty that d7 was positioned at 121.9 cm (48 inches) (or very close to 121.9 cm (48 inches)) on FWD SN #131 between May 24, 1994, and April 30, 1996. These dates correspond to the dates when lane 1 tests were conducted at drop height 4. This period of time may need to be extended slightly, if other tests were conducted along different lanes or at different drop heights. In any case, FWD tests conducted on or after June 12, 1996, indicate protocol sensor positions. Also, it was reported that the regional office moved the sensor back to the 152.4-cm (60-inch) holder at that time. FWD SN #131 was delivered to SHRP and driven to the Western Region shortly before

May 24, 1994. Evidently, all tests from the time of delivery through the end of June 1996 were conducted using the SLIC-determined d7 sensor position of 121.9 cm (48 inches) in lieu of the reported protocol position of 152.4 cm (60 inches).

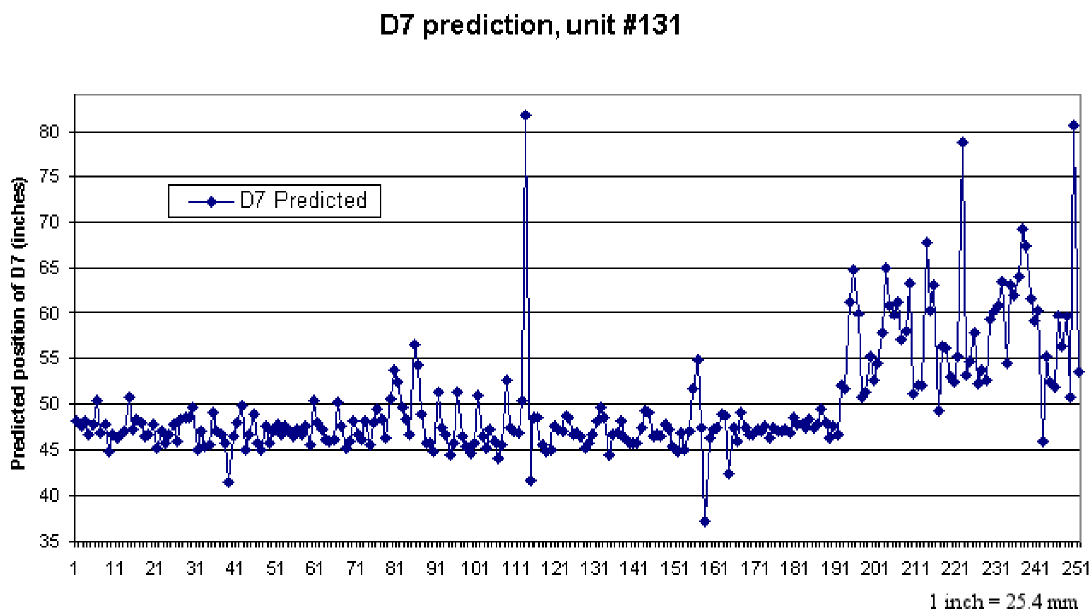


Figure 48. Graph. Predicted position of d7, unit #131, 1994–97.

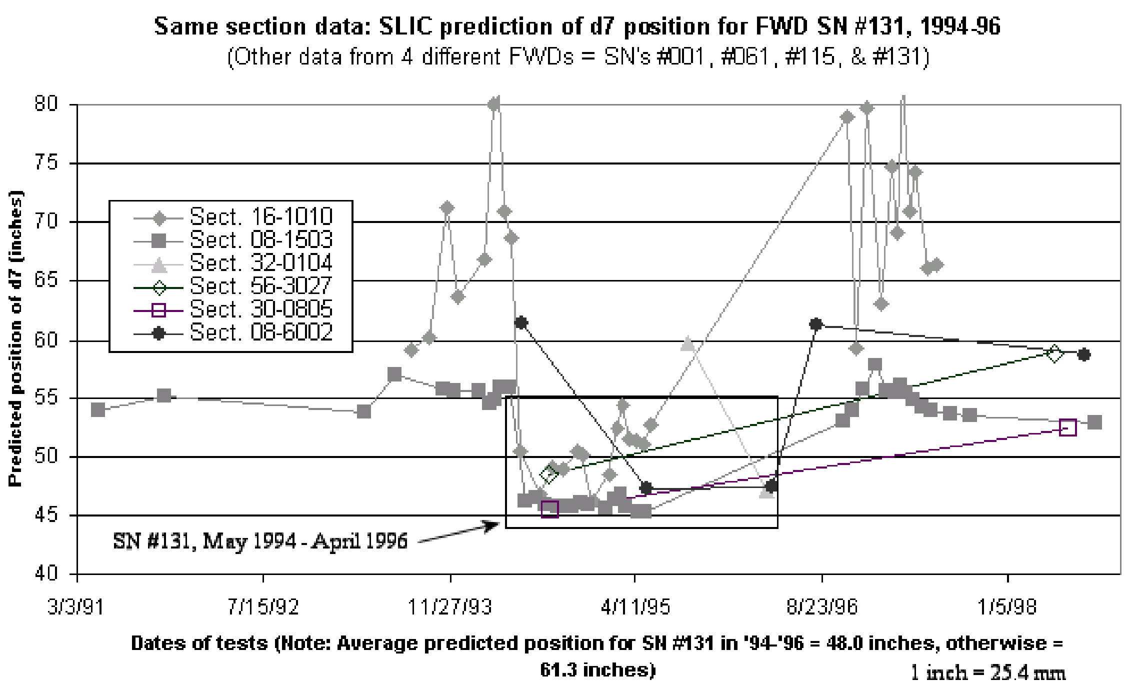


Figure 49. Graph. Same section data for d7 position, four different FWDs.

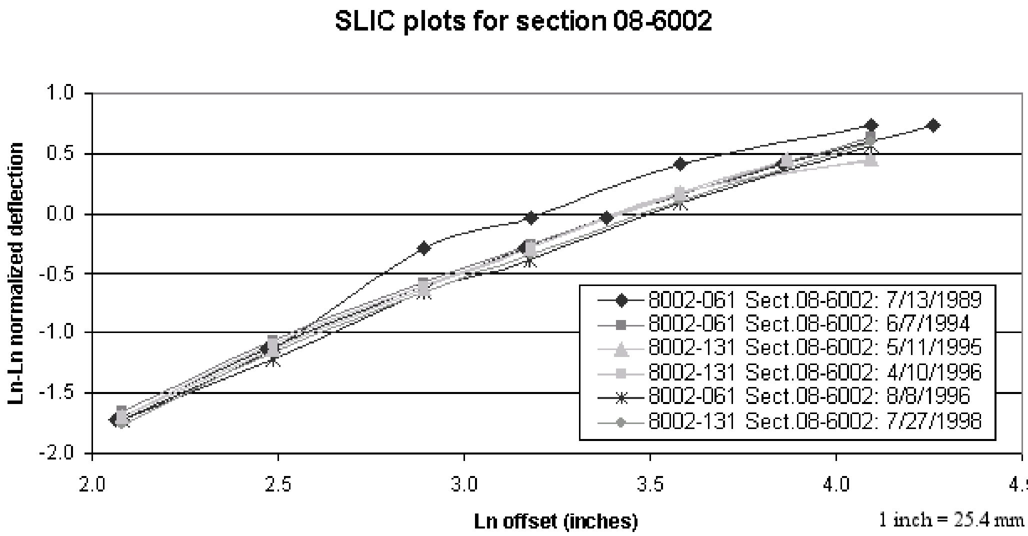


Figure 50. Graph. SLIC plots for section 08–6002 including unit #131, May 1995 and April 1996.

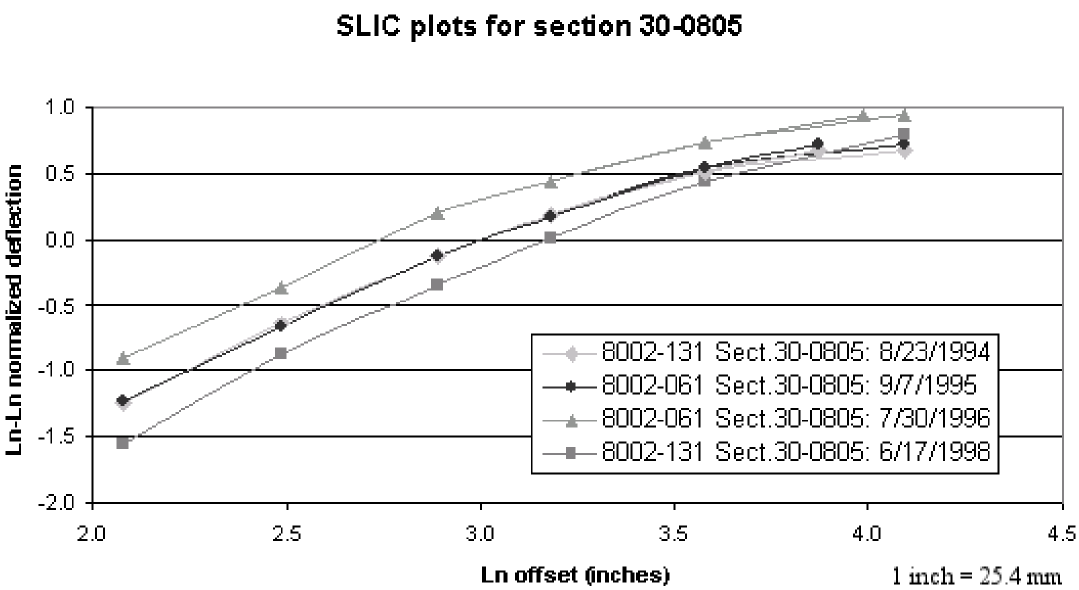


Figure 51. Graph. SLIC plots for section 30–0805 including unit #131, August 1994.

APPENDIX L. FWD SN #131, DECEMBER 16, 1997–JANUARY 20, 1998

These previously reported sensor position errors were located in the database using an automated screening version of SLIC. The SLIC screening version used was tailored for predicting the position of sensors 2 and 7. Since four or five of the sensors were positioned differently from protocol, the overall SLIC regression fits were used to verify the positioning errors found. The first two graphs shown in this appendix, (figures 52 and 53), are plots of all the SN #131 values of R^2 for the d2 and d7 regression fits, from the middle of March 1997 through the beginning of October 1998, for lane 1, drop height 4 FWD tests.

In figures 52 and 53, it can be seen that there is a serious anomaly starting around Test Sequence 107, which corresponds to December 16, 1997. The average R^2 value during the period of time in question was only 0.945, whereas when the FWD sensors used in the regression are correctly placed, the average values of R^2 for the regression is usually 0.998, or better. Clearly the R^2 values change dramatically both before and after the period of time in question. Individual plots like those shown in the succeeding three graphs corroborate that the reported (protocol) sensor configuration was incorrect.

Based on a detailed analysis of the data, for example as shown in the three succeeding figures, it is clear that the sensor positions used were 0, 8, 18, 24, 36, 48, and 66 (or 60) inches. All three section-specific plots in the last three figures of this appendix (figures 54, 55, and 56) depict these sensor positions, which correspond exactly to the sensor positions used at WesTrack just prior to December 16, 1997, *except* for d2 and d7. At WesTrack, d2 should have been placed at 30.5 cm (12 inches); however it is clear it remained unmoved at 20.3 cm (8 inches), probably from previous LTPP testing. Also at WesTrack, d7 should have been at 152.4 cm (60 inches); however, from the plots shown it appears to be at approximately 167.6 cm (66 inches). This latter value, however, is uncertain, so it is recommended that the LTPP and WesTrack d7 protocol sensor position of 152.4 cm (60 inches) still be used in the LTPP database.

In the three section-specific plots shown in figures 54, 55, and 56, the results shown graphically utilize light gray lines and data points for the erroneous data. The light gray plots show d3–d7 in both their actual and incorrect (protocol) offset positions. The plots that are parallel to the rest of the data are the correct ones, with d3 through d7 set to 18, 24, 36, 48, and 66 inches, respectively. Please note again that it is not absolutely certain that d7 is really at 167.6 cm (66 inches) because the plot with d7 at 152.4 cm (60 inches) would result in almost as good a fit.

Because of this information, and the previous information supplied to FHWA, it can be concluded with certainty that d3, d4, d5, and d6 were positioned at 18, 24, 36, and either 60 or 66 inches, respectively, between December 16, 1997, and January 20, 1998. These dates correspond to the dates when lane 1 tests were conducted at drop height 4 with SN #131. This period of time may need to be extended slightly, if other tests were conducted along different lanes or at different drop heights. In any case, FWD tests conducted with SN #131 on or before December 8, 1997, and on or after February 13, 1998, clearly show that normal LTPP protocol sensor positions were used.

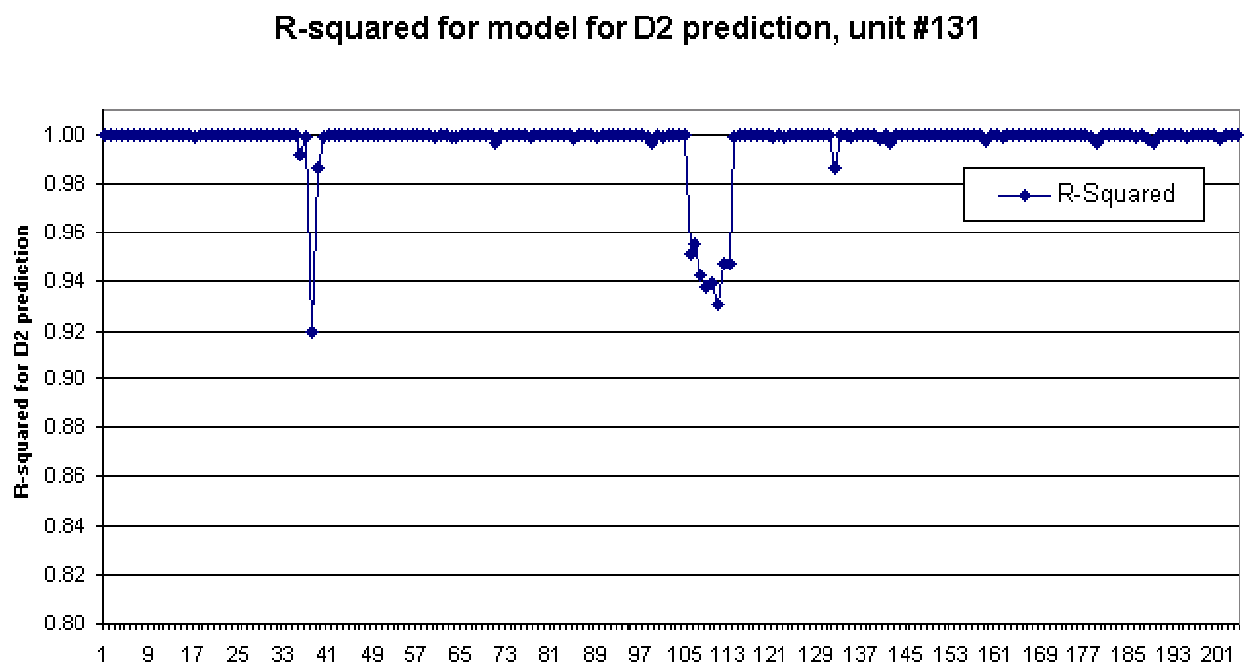


Figure 52. Graph. R-squared model for d2 prediction, unit #131, 1997–98.

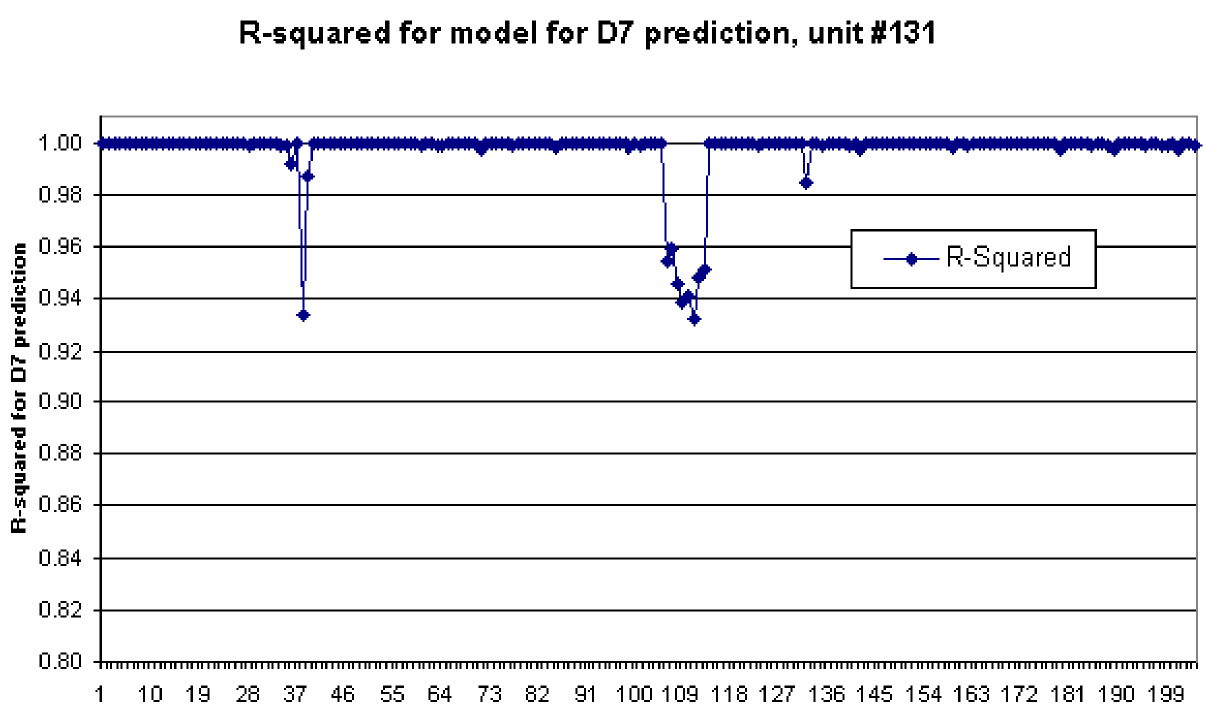


Figure 53. Graph. R-squared model for d7 prediction, unit #131, 1997–98.

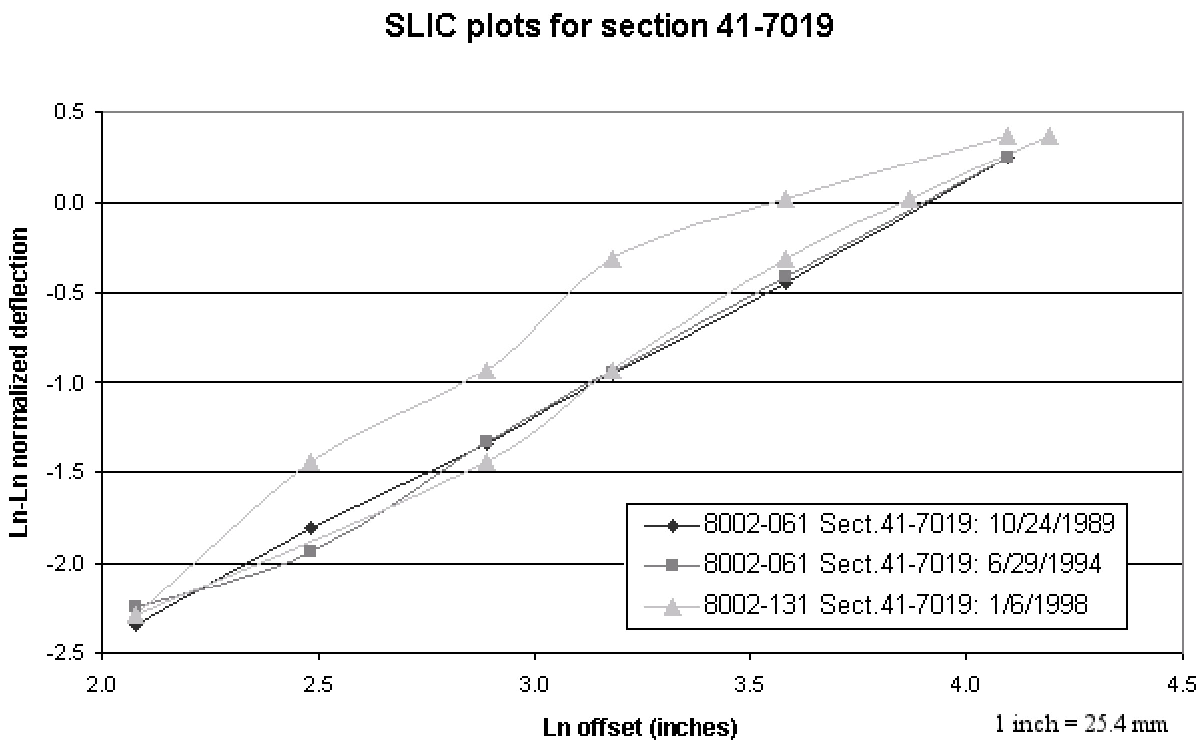


Figure 54. Graph. SLIC plots for section 41–7019 including unit #131, January 1998.

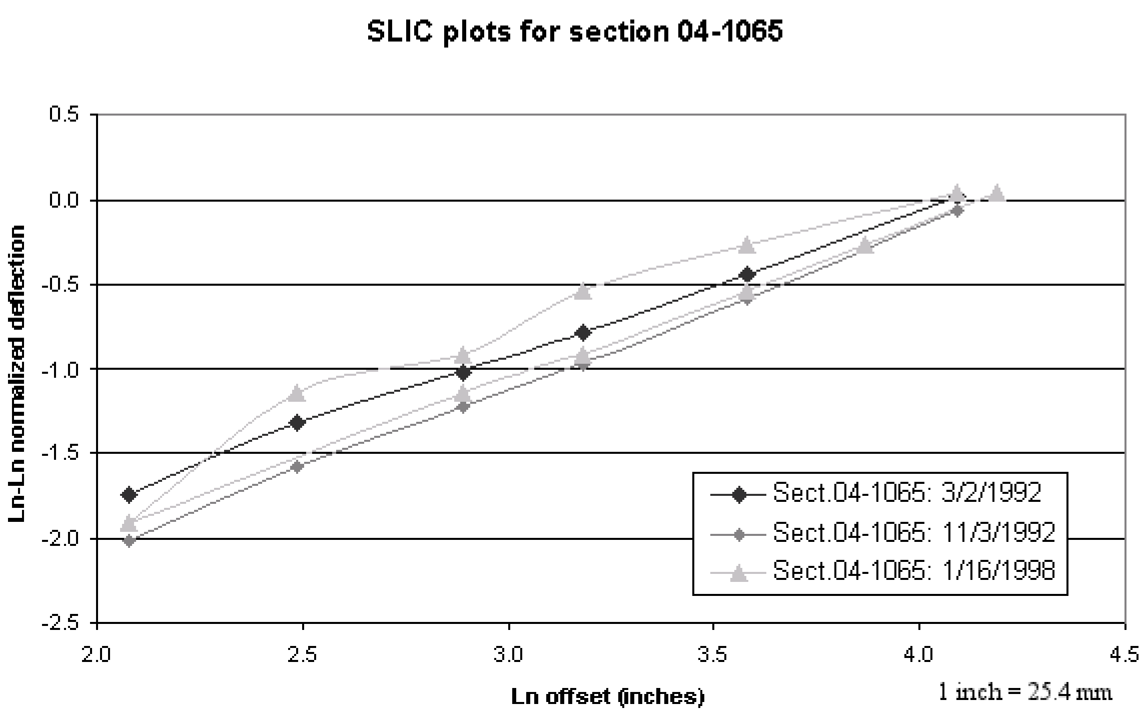


Figure 55. Graph. SLIC plots for section 04–1065 including unit #131, January 1998.

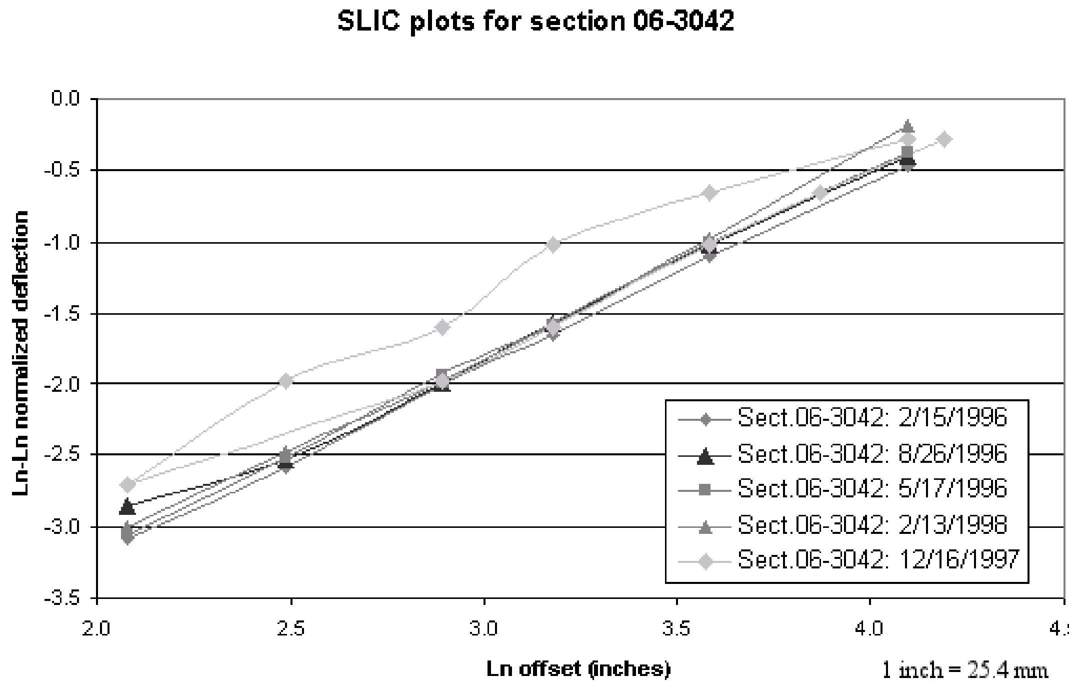


Figure 56. Graph. SLIC plots for section 06–3042 including unit #131, December 1997.

APPENDIX M. THE GENERALIZED LIKELIHOOD RATIO FOR H48 OVER H60

If two hypotheses are available for a model for data, a standard way to compare them is the generalized likelihood ratio. Briefly, this is a computation of the highest possible probability for the data under each hypothesis, or the maximum likelihood estimates of the parameters for the data within each hypothesis. The H48 hypothesis is that sensor 7 was offset 121.9 cm (48 inches); the H60 hypothesis is that sensor 7 was offset 152.4 cm (60 inches).

In each of the three cases examined below, the data to be modeled are the predicted positions of sensor 7, using all of the nonjoint associated deflection data for a particular site and day. These data fail tests of the hypothesis that they come from a normal distribution, but are approximately symmetric. The central limit theorem would then imply that the sample means have approximate normal distributions, with the approximation improving as the sample size (i.e., the number of dates) increases.

Thus the sample mean, *x* bar , is approximately normally distributed with mean μ_H and unknown standard deviation σ divided by the square root of n . Here μ_H is the appropriate value dictated by the hypothesis; if H is H48, then μ_H is 48, and if H is H60, then μ_H is 60. The nuisance parameter σ = σ_H is estimated by its maximum likelihood estimate shown in the equation given in figure 57.

$$(\Sigma\ (x - \mu_H)^2 \div n)^{1/2}.$$

Figure 57. Equation. Maximum likelihood estimate.

The likelihood under either hypothesis is shown in the equation in figure 58.

$$\frac{\sqrt{n}}{\sqrt{2\pi}\sigma_H} \exp\left[\frac{-n}{2}\left(\frac{\bar{x} - \mu_H}{\sigma_H}\right)\right]$$

Figure 58. Equation. The likelihood.

For example, if the hypothesis is H48, then the value of μ_H is replaced by 48, and the value of σ_H is replaced as shown in the equation in figure 59.

$$(\Sigma\ (x - 48)^2 \div n)^{1/2}.$$

Figure 59. Equation. Maximum likelihood estimate, σ_H = 48.

This likelihood value is computed for each hypothesis, and the ratio of these two numbers is called the likelihood ratio, a computation of the relative likelihood of the data under the two competing hypotheses.

Table 12 captures all of the relevant information for the three datasets presented in the report. MLE of SD is the maximum likelihood estimate of σ, the standard deviation, referenced above.

Table 12. Likelihood ratio stats for protocol versus nonprotocol d7 sensor positions.

FWD Serial Number	Sample Mean, $\bar{x}$	MLE of SD under H48	MLE of SD under H60	Sample Size, n	Likelihood under H48	Likelihood under H60	Likelihood Ratio
8002–129	47.99	1.88	12.16	12	0.7350095	0.0003252	2,260
8002–132	48.12	2.33	12.10	29	0.8840417	1.531E–07	5,773,093
8002–061	47.20	1.44	12.87	65	9.4002E–05	2.789E–15	33,706,837,035

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2. Lukanen, E.O., Stubstad, R.N., and Briggs, R.C. *Temperature Predictions and Adjustment Factors for Asphalt Pavement.* Federal Highway Administration Report FHWA–RD–98–085, Washington, DC, 1998.

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