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Falling-Weight Deflectometer Study: Optimizing the Number of Replicates and the Spacing of Test Stations

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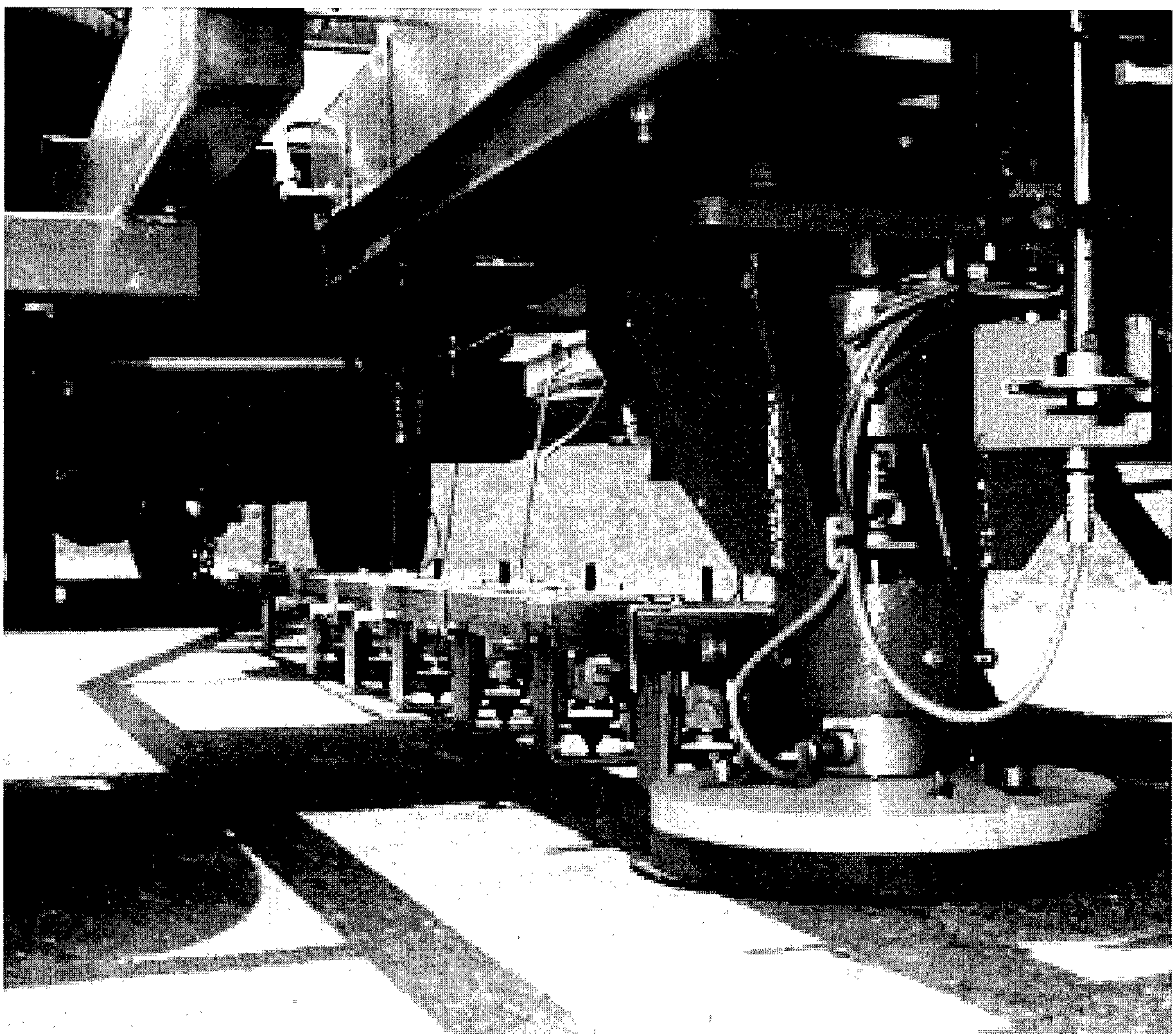
August 2001



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Falling-Weight Deflectometer Study: Optimizing the Number of Replicates and the Spacing of Test Stations

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Contents

Preface

The investigation documented in this report was sponsored by the Federal Highway Administration, U.S. Department of Transportation, through Interagency Agreement DTFH61-94-Y-00210. This research was conducted by personnel of the Airfields and Pavements Branch (APB), Geotechnical and Structures Laboratory (GSL), U.S. Army Engineer Research and Development Center (ERDC), Vicksburg, MS.

This study was conducted under the general supervision of Dr. Michael J. O'Connor, Director, GSL. Direct supervision was provided by Dr. Albert J. Bush III, Chief, APB. The principal investigator for the project was Dr. Reed B. Freeman, APB. The report was authored by Dr. Freeman and Mr. Don R. Alexander, APB.

At the time of publication of this report, Dr. James R. Houston was Director of ERDC, and COL John W. Morris III, EN, was Commander and Executive Director.

Introduction

During fiscal years 1996 and 1997, the U.S. Army Engineer Waterways Experiment Station (WES) was under contract with the Federal Highway Administration (FHWA) to provide a critical review of the Long-Term Pavement Performance (LTPP) Program, which was developed under the Strategic Highway Research Program (SHRP). Included in the scope of this study is a review of the current procedures used for conducting falling-weight deflectometer (FWD) evaluations on LTPP pavements. Specifically, WES was asked to evaluate two elements of the test procedures: (1) the number of replicate drops and (2) the longitudinal spacing of test locations (stations).

In this report, the FWD test procedures are evaluated using data collected from six asphalt concrete test sections. The selected test sections represent a wide range of structural types and climatic conditions.

Background Information

Overview of SHRP-LTPP Program

The SHRP was a unit of the National Research Council, authorized by the 1987 Highway Act (Section 128 of the Surface Transportation and Uniform Relocation Assistance Act). The SHRP was designed to last for five years (1987 to 1992) and included four research areas: (1) asphalt, (2) highway operations, (3) concrete and structures, and (4) long-term pavement performance (LTPP). The total SHRP budget was $150 million, $50 million of which was used for its LTPP component. SHRP funded the first five years of the LTPP, but the program was designed to last for a total of 20 years. In 1992, when the research phase of the SHRP concluded, the FHWA agreed to oversee the LTPP. Specifically, the Pavement Performance Division of the Office of Research and Development assumed the responsibility for the remaining 15 years. The Pavement Performance Division is located at the Turner-Fairbank Highway Research Center in McLean, Virginia. Additional funding for the LTPP has been provided by states and by the Intermodal Surface Transportation Efficiency Act of 1991. At its conclusion, the LTPP will probably end up costing about $250 million (Crawley 1997).

The goal for the LTPP is "to increase pavement life by investigating various designs of pavement structures and rehabilitated pavement structures, using different materials and under different loads, environments, subgrade soil, and maintenance practices (TRB 1986)." A major component of the LTPP is the development of a National Pavement Performance Database (NPPDB), which will contain inventory information and performance histories of pavements with various design features, materials, traffic loads, environmental conditions, and maintenance practices (Hadley 1994). The NPPDB is included within the LTPP Information Management System (LTPP IMS).

The pavements that are included in the LTPP can be classified into two groups: General Pavement Study (GPS) test sections and Specific Pavement Study (SPS) test sections. The GPS sections include in-service pavements, selected on the basis of their ability to contribute to nine established GPS studies. These studies include asphalt concrete pavements, portland cement concrete pavements, and overlays. The chosen pavement sections were limited to those that were both in common use and reflected standard engineering practices. The GPS plan includes approximately 1100 pavement test sections (FHWA 1996). Test sections are generally 152 m (500 ft) in length.

The SPS sections were established to serve as components of relatively concise experiments intended to improve pavement performance prediction and to contribute to new pavement design methods. Relative to the GPS program, the SPS program was expected to involve more specific goals and was expected to provide data that could not be provided by the GPS pavements. For example, drainage methods could not be properly studied using GPS sections because the desired range of methods could not be found among existing pavements (FHWA 1996). The SPS sections were constructed or rehabilitated through a cooperative effort with interested state highway agencies. The SPS plan includes approximately 1600 pavement test sections, built at 200 locations (FHWA 1996).

Within both the GPS and the SPS, 64 test sections were designated as members of the Seasonal Monitoring Program (SMP). The primary objective of the SMP is to provide information on variations in temperature and moisture content within a pavement structure. The sites are divided into two groups and each group is monitored intensively in alternate years.

Four regional contractors were employed to coordinate and communicate LTPP-related activities across the United States and Canada. Each region included a group of states and/or provinces in its jurisdiction, with test sections located throughout the defined boundaries. The regions were defined primarily on the basis of climatic considerations, with region boundaries adjusted to correspond to state and provincial boundaries, as shown in Figure 1. The states and Canadian provinces in each region are listed in Table 1. The North Atlantic region corresponds to the wet-freeze zone used by the American Association of State Highway and Transportation Officials (AASHTO). The Southern region is primarily a wet-nonfreeze zone, while the North Central region is primarily a wet-freeze zone. The Western region contains both dry-freeze and dry-nonfreeze areas (Hadley 1994).

Within the LTPP IMS structure, the regional offices are responsible for most of the collection and entry of data. They are also responsible for administering quality control for these data. A technical assistance contractor (TAC) supervises the central IMS and is responsible for the collection, entry, and quality control for climatic data. The TAC is also responsible for providing data to the public (FHWA 1996).

The LTPP IMS has test section information organized into seven data modules: inventory, materials testing, climate, maintenance, rehabilitation, traffic, and monitoring. Each module has multiple tables, representing a collection of related information. The falling-weight deflectometer data is included within the monitoring module, along with longitudinal and cross profiles, friction data, and distress data. Some collected data are not available directly from the IMS database, either because they are not considered of general interest or because they are too large for on-line storage. The three sets representing the largest volume of off-line data are (FHWA 1996):

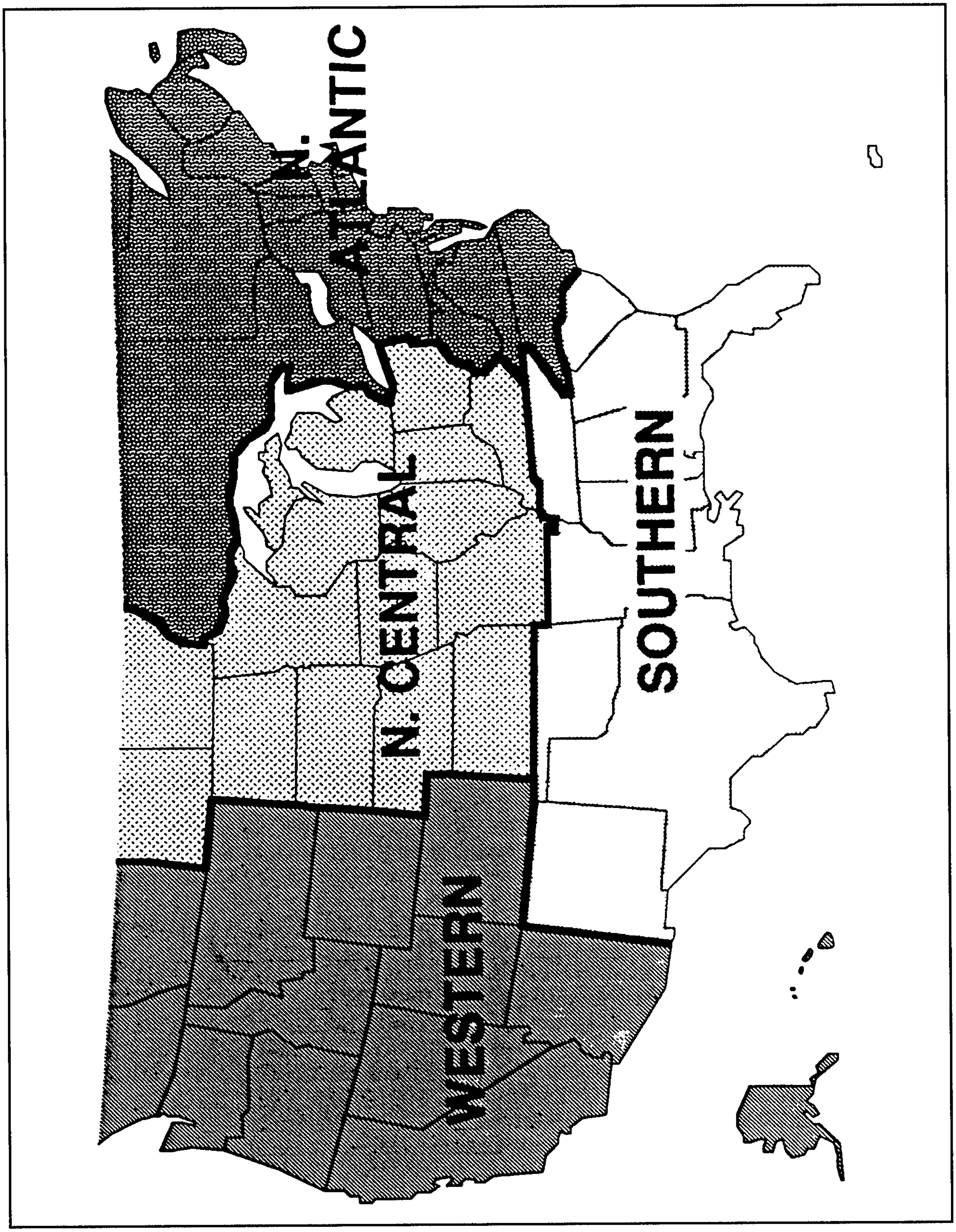

Figure 1. SHRP-LTPP regional boundaries (Hadley 1994)

Table 1 States and Canadian Provinces Within SHRP Regions	
Region	**State or Province**
North Atlantic (NA)	CT, DC, DE, MA, MD, ME, NC, NH, NJ, PA, RI, VA, VT, WV, NB, NF, NS, ON, PE, PQ
North Central (NC)	IA, IL, IN, KS, KY, MI, MN, MO, ND, NE, OH, SD, WI, MB, SK
Southern (S)	AL, AR, FL, GA, LA, MS, NM, OK, PR, SC, TN, TX
Western (W)	AK, AZ, CA, CO, HI, ID, MT, NV, OR, UT, WA, WY, AB, BC

a. Falling-weight deflectometer time history data.

b. Raw traffic data in the form of hourly counts and vehicle weight records.

c. Climatic data.

Current Falling-Weight Deflectometer Evaluation Procedures

The falling-weight deflectometers, as specified by SHRP, are manufactured by Dynatest Corporation and are capable of measuring deflections at seven radial distances from the impulse load. The impulse load can vary from approximately 11.1 kN (2500 lb) to 120 kN (27000 lb). The falling-weight deflectometers are used for two general types of testing: deflection basin measurements and load transfer measurements. Deflection basin testing is performed on both flexible and rigid pavements. Load transfer testing is performed only on rigid pavements. The configuration of deflection sensors for different test types are shown in Figure 2.

Falling-weight deflectometer testing for flexible pavements includes four drop heights, intended to achieve the target loads shown in Table 2. Testing for rigid pavements includes three drop heights, which are intended to achieve the highest three target loads shown in Table 2 (h_2 through h_4). After arriving at a test section, operators are instructed to select a point on the pavement outside of the test section to experiment with the drop-height/load-level settings until the target loads are achieved. These drop heights then remain constant throughout the test section. Because the load range prescribed for SHRP-LTPP testing does not exceed 71.2 kN (16000 lb), only the "200 kg" mass system in the FWD is necessary. Operators are instructed to keep the mass at this setting (FHWA 1989).

Falling-weight deflectometer tests for flexible and rigid pavements include the drop sequences shown in Table 3. If either flexible or rigid pavements have multiple lanes for a single direction of traffic, falling-weight deflectometer tests are performed in the slow-traffic lane (closest to the shoulder). For flexible pavements, deflection basin tests will be performed in two passes, one at midlane and one in the outer wheelpath. Midlane tests are performed 1.8 m (6 ft) from the pavement edge, while outer-wheelpath tests are performed 0.76 m (2.5 ft) from the pavement edge. Test sections are 152 m (500 ft) in length and falling-weight deflectometer tests are generally performed every 15.2 m (50 ft) for each pass.

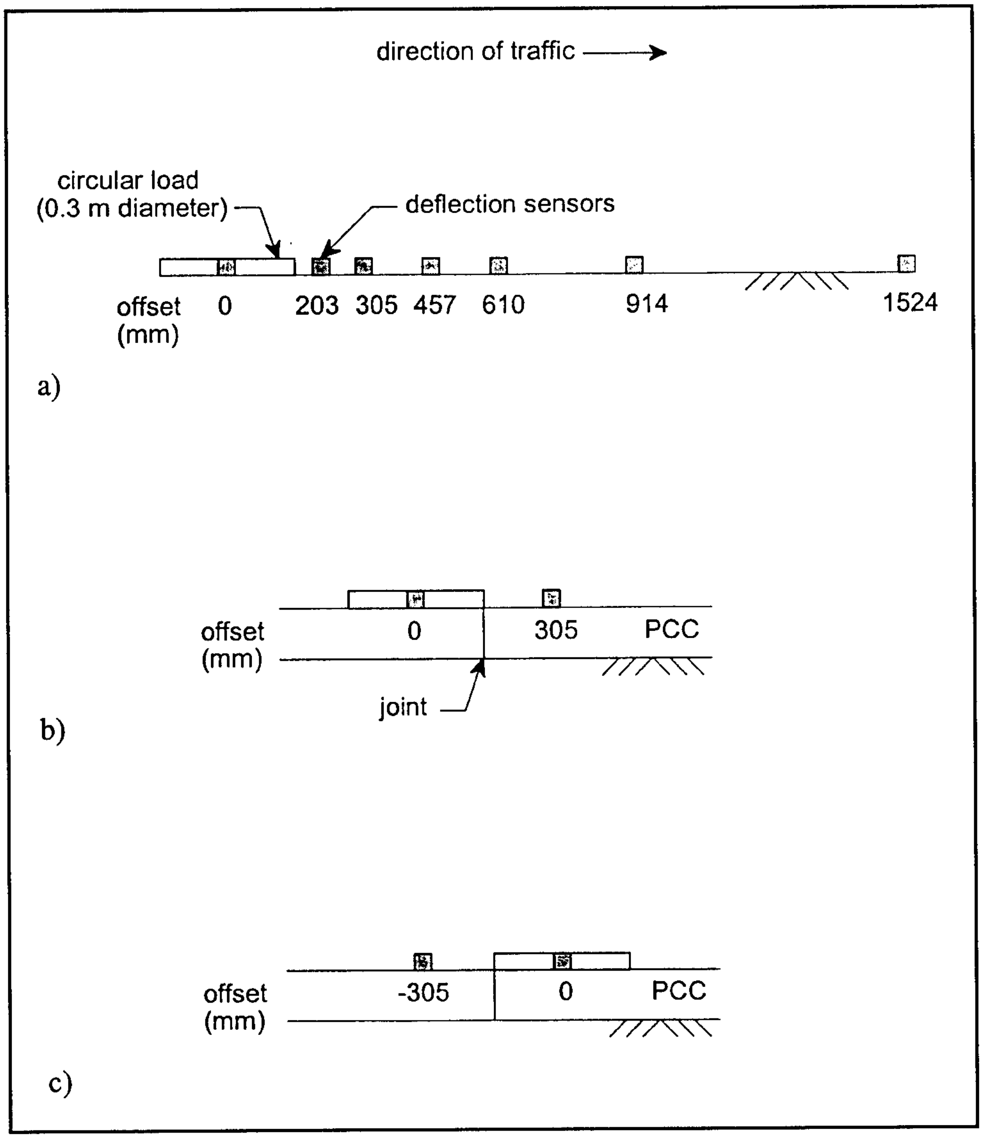

Figure 2. Deflection sensor configurations for (a) basin tests, (b) leave slab load transfer tests, and (c) approach slab load transfer

Table 2
Drop Heights and Target Loads (FHWA 1989)

Drop Height	Target Load, kN (lbs)	Target Tolerance
h_1 (lowest)	26.7 (6,000)	±10%
h_2	40.0 (9,000)	±10%
h_3	53.4 (12,000)	±10%
h_4 (highest)	71.2 (16,000)	±10%

Table 3
Drop Sequences for Falling-Weight Deflectometer Tests (FHWA 1989)

No. in Sequence	No. of Drops	Drop Height	Remarks
Flexible Pavements			
1	3	h_3	Note #1
2	4	h_1	Note #2
3	4	h_2	Note #2
4	4	h_3	Note #2
5	4	h_4	Note #2
Rigid Pavements			
1	3	h_3	Note #1
2	4	h_2	Note #2
3	4	h_3	Note #2
4	4	h_4	Note #2
Note #1: Drops used for seating only; no data recorded. Note #2: Store peak deflections for all drops; store complete deflection time-history for the fourth drop.			

Sites that are considered to be part of the Seasonal Monitoring Program are an exception. For these sites, falling-weight deflectometer tests are performed every 7.6 m (25 ft).

Rigid pavements are tested with a total of three passes. The first two passes (midlane and pavement-edge) are used to collect deflection basin measurements. The third pass (outer wheelpath) is used to collect load transfer measurements. Offsets from pavement edge for midlane and outer-wheelpath tests are each the same as those used for flexible pavements. Each rigid pavement slab is tested five times:

a. The midlane test is performed at midslab.

b. Pavement edge tests are performed both at the first corner and at midslab.

c. Two load transfer tests are performed at each joint (a "leave-slab test" and an "approach-slab test").

Rigid pavement test sections are also 152 m (500 ft) in length. The number of falling-weight deflectometer tests performed within a given test section depends on joint spacing and the presence of transverse cracks. If a full-depth, transverse crack exists at or near the middle of a slab, the slab should be considered as two "effective" slabs. A maximum of 20 "effective" slabs are evaluated for each pavement test section.

During falling-weight deflectometer evaluations, additional data collected include the date and time of tests and temperatures for both the air and the pavement surface. In addition, any observed distress is noted.

The frequency for performing falling-weight deflectometer evaluations varies, depending on the type of test section (General Pavement Studies or Specific Pavement Studies and whether or not it is part of the Seasonal Monitoring Program). Pavements that are part of the Seasonal Monitoring Program are evaluated most often. Falling-weight deflectometer evaluations for the SMP pavements are generally performed at least monthly. Sometimes multiple evaluations are performed within a single month. In many cases, multiple evaluations are performed during a single day in order to capture the effect of changing temperatures. As a consequence of the frequency of testing for these sites, however, only a portion of the test sections are evaluated. Typically, SMP pavement evaluations include 61.0 m (200 ft) of their length (either from station 0 to 200 or from station 300 to 500).

Test Sections

Falling-weight deflectometer (FWD) test results were analyzed for six test sections from the Long-Term Pavement Performance (LTPP) study of the Strategic Highway Research Program (SHRP). All six test sections are part of both the SHRP-LTPP General Pavement Study and the SHRP-LTPP Seasonal Monitoring Program. The test sections were selected in a manner to provide a range of FWD responses. Two test sections were selected from each of three SHRP climatic regions (wet-freeze, wet-no freeze, and dry-freeze), as shown in Table 4. The two selected test sections from each region offered different structural characteristics, as shown in Table 5. Future references to the test sections will be by state and abbreviated test section identification number: MA 1002, VT 1002, TX 1060, TX 1122, MT 8129, and UT 1001.

This report presents results in two parts: a replicate study and a station-spacing study. The data used for the two studies were obtained from two different sources. The data for the replicate study was obtained from the FHWA Information Management System (IMS), while the data for the station-spacing study was obtained directly from the regional contractors. Consequently, the range of dates used in the two studies is different in some cases. The data for the replicate study include pavement evaluations performed from November 1992 through June 1995. The data used for the station-spacing study include pavement evaluations performed from September 1992 through June 1997. The durations of data for the various test sections range from 1-1/2 to 2-1/2 years in the replicate study. The durations of data for the station-spacing study range from 1-1/2 to 4-1/2 years.

On each date of testing, the pavement was evaluated up to six times. Each evaluation included FWD tests along one or both of the two test paths (midlane and/or outside wheelpath). Each evaluation included nine test stations spaced at 7.6 m (25 ft), either station 0 through 200 or station 300 through 500.

Air temperatures and pavement surface temperatures were measured during FWD pavement evaluations. These data were obtained from the FHWA IMS and are shown in Appendix A. The extreme temperatures encountered during testing

Table 4
Inventory Data for the Seasonal Monitoring Program Test Sections (FHWA 1997)

Characteristic	SHRP Climatic Region					
	Wet-freeze		Wet-no freeze		Dry-freeze	
State	MA	VT	TX	TX	MT	UT
Section ID Number[a]	251002.1	501002.1	481060.1	481122.1	308129.1	491001.1
Functional Class	rural interstate	rural primary artery	rural primary artery	rural primary artery	rural primary artery	rural minor artery
County Code	13	1	391	493	37	37
Route Number	391	7	77	181	12	191
Milepost	1.95	5.11	1.96	0	137	23.74
Elevation, m (ft)	27 (88)	86 (283)	24 (78)	154 (505)	1350 (4440)	1340 (4380)
Latitude	42.17	44.12	28.51	29.24	46.31	37.28
Longitude	72.61	73.18	97.06	98.25	109.13	109.59
Freezing Index (°F-days)	633	1379	6	12	1121	249
Precipitation, mm (in.)	(46)	(41)	(33)	(24)	(12)	(9)
No. of Freeze/ Thaw Cycles	112	99	9	27	145	139
Days Above 32°C (90°F)	10	1	96	121	24	75
Days Below 0°C (32°F)	133	157	9	24	171	139
No. of Wet Days	139	192	108	90	92	45

[a] First two digits = state code; remaining digits = test section number
Note: Climatic information represents yearly averages, which were calculated with data collected over a period ranging from 3 to 11 years.

Table 5
Structural Characteristics for the Seasonal Monitoring Program Test Sections (FHWA 1997)

SHRP Climatic Region	Section ID Number[a] (State)	Pavement Layer		
		Surface Courses[b]	Base/Subbase Courses	Subgrade
wet-freeze	251002.1 (MA)	36 mm DGAC 160 mm DGAC	100 mm crushed gravel 210 mm soil-aggregate	poorly-graded sand and silt
	501002.1 (VT)	76 mm DGAC 140 mm DGAC	660 mm crushed gravel	poorly-graded gravel, silt, and sand
wet-no freeze	481060.1 (TX)	43 mm DGAC 150 mm DGAC	310 mm crushed stone 150 mm lime-treated soil	silty sand
	481122.1 (TX)	10 mm chip seal 36 mm DGAC 41 mm DGAC	400 mm soil-aggregate	8.4 in. fine-grained clayey sand
dry-freeze	308129.1 (MT)	5 mm chip seal 76 mm DGAC	580 mm crushed gravel	gravelly lean clay and sand
	491001.1 (UT)	10 mm chip seal 130 mm DGAC	150 mm soil-aggregate	silty sand

[a] First two digits = state code; remaining digits = test section number.
[b] DGAC = dense-graded asphalt concrete.

at each site are summarized in Table 6. The pavement surface temperature fell below freezing for the test sections in Massachusetts, Vermont, Montana, and Utah. The hottest pavement surface temperatures were encountered in Texas and Utah, where temperatures reached 55 °C (131 °F) or higher. The pavement in Utah experienced the widest range of temperatures: 63 °C (145 °F).

Table 6
Extreme Temperatures Encountered During FWD Testing

Test Section	Air Temperature (°C)			Pavement Surface Temperature (°C)		
	Low	High	Range	Low	High	Range
MA 1002	1	36	35	-7	50	57
VT 1002	-9	42	51	-6	49	55
TX 1060	0	41	41	5	55	50
TX 1122	4	41	37	5	59	54
MT 8129	-10	40	50	-13	46	59
UT 1001	-3	47	50	-4	59	63

Falling-Weight Deflectometer Replicate Study

The variability between replicates for FWD tests was characterized using measured deflections at each sensor. Because the same target loads were used for the FWD tests at each test section, the magnitudes of deflection experienced were expected to be different for the various pavement structures. In order to obtain an idea of the relative magnitudes of deflection experienced on the various pavements, all deflection measurements for each site were summarized, as shown in Tables 7 through 12. Each table provides median, skew, and 95th percentile statistics for all measured deflections for a particular pavement test section. These deflection data were collected on the evaluation dates shown in Table 13. Most dates included multiple pavement evaluations, as shown by the numbers in parentheses in Table 13.

A review of Tables 7 through 12 shows that the deflections at each sensor increased two- to three-fold as target load increased from 26.7 kN to 71.2 kN. The deflection decreased two- to seven-fold as sensor offset from load increased from 0 mm to 1524 mm. The test sections rank in the following order, from smallest deflections to largest: TX 1122, TX 1060, VT 1002, MA 1002, UT 1001, MT 8129.

Normalized Deflection

In order to properly evaluate the repeatability of FWD tests using deflection measurements, the slight variability in load between replicate drops must be eliminated from the analysis. The measured force between replicate drops changes slightly (on the order of 1.5 percent or less) due to variabilities associated with the velocity of mass at impact and material response. These slight changes in load would be considered within any techniques of reducing FWD data for the purpose of monitoring pavement performance, so they should not be included in this analysis concerning the repeatability of deflection measurements. Measured deflections were therefore adjusted (or "normalized") as follows:

$$y^* = y \times \frac{\text{target load}}{\text{applied load}} \tag{1}$$

Table 7
Statistics for Measured Deflections (in microns) for Test Section 1002 in Massachusetts

Sensor Offset	Statistic	Target Load (kN) 26.7	40.0	53.4	71.2
0 mm	median	146	216	280	351
	skewness	-0.425	-0.485	-0.561	-0.543
	95th percentile	208	304	385	482
203 mm	median	121	181	235	294
	skewness	-1.55	-1.66	-1.79	-1.90
	95th percentile	149	219	277	342
305 mm	median	105	158	204	257
	skewness	-2.12	-2.28	-2.39	-2.55
	95th percentile	123	182	232	287
457 mm	median	85	128	166	210
	skewness	-2.77	-2.95	-2.99	-3.16
	95th percentile	96	142	184	229
610 mm	median	68	105	136	173
	skewness	-2.54	-2.89	-2.92	-3.09
	95th percentile	78	116	151	189
914 mm	median	45	70	92	118
	skewness	-1.21	-1.53	-1.59	-1.72
	95th percentile	53	80	105	133
1524 mm	median	22	34	45	59
	skewness	5.60	5.84	0.67	-1.69
	95th percentile	27	42	55	71

Note: Data includes 3960 deflection measurements for each combination of target load and sensor offset.

where

y^* = peak deflection adjusted for applied load (micrometers)

y = measured peak deflection (micrometers)

target load = load targeted by set drop height (kN), as shown in Table 2

applied load = measured peak load (kN)

Repeatability Calculations

Replicate deflection variability was evaluated for each of the seven FWD deflection sensors, at each of the four FWD target loads (drop heights). The number of FWD tests available for each target load ranged from 980 to 1418 for the various test sections. Each FWD test consisted of four replicate drops.

Table 8
Statistics for Measured Deflections (in microns) for Test Section 1002 in Vermont

Sensor Offset	Statistic	Target Load (kN) 26.7	40.0	53.4	71.2
0 mm	median	128	193	254	327
	skewness	-0.095	-0.209	-0.346	-0.386
	95th percentile	218	318	405	520
203 mm	median	107	162	212	274
	skewness	-1.18	-1.25	-1.38	-1.39
	95th percentile	148	221	287	368
305 mm	median	93	142	185	241
	skewness	-1.71	-1.72	-1.80	-1.78
	95th percentile	119	181	235	306
457 mm	median	76	116	153	200
	skewness	-1.95	-2.01	-2.04	-1.99
	95th percentile	95	143	188	250
610 mm	median	63	96	128	169
	skewness	-2.19	-2.21	-2.21	-2.14
	95th percentile	76	116	156	206
914 mm	median	46	69	93	123
	skewness	4.87	4.11	2.61	1.05
	95th percentile	56	84	113	151
1524 mm	median	28	42	56	74
	skewness	5.40	5.17	3.64	2.57
	95th percentile	35	51	68	90

Note: Data includes 4088 deflection measurements for each combination of target load and sensor offset.

The distributions for the coefficient of variation between replicates were positively skewed with minimum values at or near zero. Median, skewness, and 95th percentile statistics for these distributions are shown for each of the test sections in Tables 14 through 19. All median values for coefficients of variation were less than 5 percent and all 95th percentile values were less than 10 percent. In general, variability increased as mean deflection decreased. Both a decrease in drop height and an increase in sensor offset from the load caused increases in variability between replicates.

The next step in the study was to establish a relationship between the number of FWD replicates and the resulting confidence in the mean measured deflection. The permissible difference between measured mean deflection and true deflection can be represented as a percent error term, E.

$$E = \frac{|\bar{y}^* - \mu|}{\mu} \times 100\% \qquad (2)$$

Table 9
Statistics for Measured Deflections (in microns) for Test Section 1060 in Texas

Sensor Offset	Statistic	Target Load (kN) 26.7	40.0	53.4	71.2
0 mm	median	104	154	203	264
	skewness	1.01	1.01	1.03	1.02
	95th percentile	151	227	299	386
203 mm	median	90	133	175	227
	skewness	0.954	0.952	0.984	0.989
	95th percentile	129	192	254	330
305 mm	median	82	121	160	207
	skewness	0.924	0.916	0.947	0.956
	95th percentile	116	173	230	300
457 mm	median	73	108	143	186
	skewness	0.894	0.879	0.924	0.932
	95th percentile	102	152	203	264
610 mm	median	66	97	128	166
	skewness	0.829	0.837	0.893	0.917
	95th percentile	89	134	178	233
914 mm	median	55	81	106	137
	skewness	0.767	0.795	0.880	0.928
	95th percentile	72	106	142	185
1524 mm	median	40	58	76	96
	skewness	0.639	0.698	0.871	0.981
	95th percentile	49	72	94	120

Note: Data includes 4656 deflection measurements for each combination of target load and sensor offset.

where

$\bar{y}^*$ = calculated mean for measured (and adjusted) deflections

μ = true mean

Considering the large number of test results, a level of confidence and its dependence on the number of replicates will be invoked using the standard normal (Z) distribution for measured means (Freund and Wilson 1993):

$$z = \frac{|\bar{y}^* - \mu|}{\frac{\sigma}{\sqrt{n}}} \tag{3}$$

where

z = standard normal value from a population with mean = 0 and $\sigma = 1$

Table 10
Statistics for Measured Deflections (in microns) for Test Section 1122 in Texas

Sensor Offset	Statistic	Target Load (kN) 26.7	40.0	53.4	71.2
0 mm	median	81	126	168	222
	skewness	0.603	0.394	0.381	0.382
	95th percentile	110	161	212	277
203 mm	median	49	76	102	135
	skewness	0.561	0.626	0.698	0.769
	95th percentile	65	100	134	179
305 mm	median	38	59	80	108
	skewness	0.605	0.657	0.746	0.819
	95th percentile	51	78	105	140
457 mm	median	31	48	65	86
	skewness	0.576	0.588	0.626	0.708
	95th percentile	40	61	83	110
610 mm	median	26	40	54	72
	skewness	0.554	0.432	0.405	0.442
	95th percentile	34	51	67	90
914 mm	median	20	31	41	55
	skewness	0.593	0.437	0.393	0.314
	95th percentile	27	39	52	67
1524 mm	median	13	21	27	36
	skewness	0.539	0.426	0.378	0.206
	95th percentile	20	27	35	45

Note: Data includes 5584 deflection measurements for each combination of target load and sensor offset.

σ = known standard deviation for deflection measurements

n = number of replicates with which each mean deflection ($\bar{y}$*) is calculated

Hence, designating "E" as the error,

$$z = \frac{(E \cdot \mu)\sqrt{n}}{\sigma \cdot 100\%} \tag{4}$$

which yields:

$$\frac{\sigma}{\mu} \times 100\% = \frac{E\sqrt{n}}{z} \tag{5}$$

Now the left-hand term is the coefficient of variation (CV), which was summarized above for the various test sections.

Table 11
Statistics for Measured Deflections (in microns) for Test Section 8129 in Montana

Sensor Offset	Statistic	Target Load (kN) 26.7	40.0	53.4	71.2
0 mm	median	381	518	666	835
	skewness	-0.608	-0.659	-0.695	-0.700
	95th percentile	505	670	839	1046
203 mm	median	294	404	524	664
	skewness	-0.709	-0.738	-0.766	-0.766
	95th percentile	367	502	640	801
305 mm	median	229	320	421	538
	skewness	-0.738	-0.759	-0.785	-0.785
	95th percentile	289	405	518	649
457 mm	median	164	235	312	401
	skewness	-0.763	-0.776	-0.805	-0.803
	95th percentile	207	295	386	492
610 mm	median	124	180	243	316
	skewness	-0.805	-0.802	-0.832	-0.815
	95th percentile	155	224	297	386
914 mm	median	85	123	167	221
	skewness	-0.896	-0.820	-0.854	-0.860
	95th percentile	101	152	204	264
1524 mm	median	56	83	110	140
	skewness	-0.459	-0.623	-0.542	-0.317
	95th percentile	75	105	145	201

Note: Data includes 5672 deflection measurements for each combination of target load and sensor offset.

$$E = \frac{CV \cdot z}{\sqrt{n}} \qquad (6)$$

where E and CV are both percentages.

In order to complete calculations for maximum error (E), both the appropriate CVs and a desired level of confidence for the solutions must be established. The appropriate CVs were selected as the 95th percentile values, which were presented in Tables 14 through 19. These values were viewed as appropriately conservative. The desired overall level of confidence affects the selection of the appropriate standard normal value (z). A confidence level of 95 percent was chosen, which necessitates the use of $z_{0.025}$ (two-tail), equal to 1.96. Using $z_{0.025}$ (two-tail) implies that the standard normal distribution used in the solution encompasses all but 5.0 percent of expected cases (2.5 percent in each of two tails).

Table 12
Statistics for Measured Deflections (in microns) for Test Section 1001 in Utah

Sensor Offset	Statistic	Target Load (kN) 26.7	40.0	53.4	71.2
0 mm	median	253	370	490	612
	skewness	0.715	0.598	0.566	0.635
	95th percentile	413	571	746	958
203 mm	median	224	325	434	538
	skewness	0.416	0.293	0.263	0.377
	95th percentile	333	460	602	776
305 mm	median	200	292	388	484
	skewness	0.229	0.110	0.083	0.220
	95th percentile	281	392	515	667
457 mm	median	166	240	320	401
	skewness	-0.071	-0.152	-0.174	-0.035
	95th percentile	215	307	404	520
610 mm	median	135	197	262	329
	skewness	-0.280	-0.288	-0.318	-0.209
	95th percentile	168	242	321	410
914 mm	median	90	133	179	226
	skewness	-0.288	-0.197	-0.234	-0.237
	95th percentile	110	168	220	275
1524 mm	median	52	77	103	132
	skewness	0.584	0.409	0.481	0.535
	95th percentile	74	104	143	190

Note: Data includes 3920 deflection measurements for each combination of target load and sensor offset.

Maximum error for the mean deflection was estimated for each FWD sensor, for each target load, and for replicate drops of 1, 2, 3, and 4. These estimated errors, given as percent deflection, are summarized in the figures contained in Appendix B.

Data from the test section in Massachusetts will be used to demonstrate the calculation of maximum error for mean measured deflections. Specifically, maximum error will be calculated for the deflection sensor that was offset from the load by 1524 mm, under a target load of 26.7 kN. From Table 14, the 95th percentile for coefficient of variation between replicates was 6.4 percent. If four replicates are used, the maximum error is:

$$E = \frac{CV \cdot z}{\sqrt{n}} = \frac{6.4 \times 1.96}{\sqrt{4}} = 6.3\% \quad (7)$$

If one replicate is used, the maximum error is:

Table 13
FWD Evaluations Used for the Study Concerning Replicate Drops

MA 1002	VT 1002	TX 1060	TX 1122	MT 8129	UT 1001
01 Sep. 93 (3)	07 Oct. 93 (3)	30 Nov. 93 (1)	23 Nov. 93 (5)	12 Nov. 92 (4)	06 Aug. 93 (5)
16 Nov. 93 (3)	08 Nov. 93 (2)	01 Dec. 93 (2)	27 Dec. 93 (4)	06 Dec. 92 (4)	04 Nov. 93 (2)
23 Dec. 93 (3)	20 Dec. 93 (2)	20 Jan. 94 (2)	25 Jan. 94 (2)	23 Feb. 93 (3)	02 Dec. 93 (4)
16 Feb. 94 (3)	12 Jan. 94 (1)	24 Feb. 94 (3)	25 Feb. 94 (4)	12 Mar. 93 (3)	14 Jan. 94 (5)
09 Mar. 94 (1)	02 Mar. 94 (1)	10 Mar. 94 (2)	08 Mar. 94 (1)	23 Mar. 93 (5)	11 Feb. 94 (5)
29 Mar. 94 (4)	22 Mar. 94 (1)	21 Apr. 94 (2)	15 Apr. 94 (6)	23 Apr. 93 (5)	25 Mar. 94 (5)
20 Apr. 94 (4)	13 Apr. 94 (2)	23 May 94 (4)	11 May 94 (4)	12 May 93 (3)	08 Apr. 94 (5)
11 May 94 (4)	04 May 94 (3)	07 Jun. 94 (4)	06 Jun. 94 (5)	25 Jan. 94 (4)	28 Apr. 94 (4)
08 Jun. 94 (4)	25 May 94 (3)	06 Jul. 94 (5)	05 Jul. 94 (6)	31 Mar. 94 (5)	17 Jun. 94 (4)
29 Jun. 94 (4)	22 Jun. 94 (4)	02 Aug. 94 (5)	01 Aug. 94 (6)	20 Apr. 94 (4)	15 Jul. 94 (5)
27 Jul. 94 (4)	20 Jul. 94 (4)	07 Sep. 94 (5)	06 Sep. 94 (5)	05 May 94 (3)	09 Sep. 94 (4)
01 Feb. 95 (3)	17 Aug. 94 (4)	11 Oct. 94 (4)	10 Oct. 94 (5)	06 Jun. 94 (4)	20 Oct. 94 (2)
01 Mar. 95 (3)	21 Sep. 94 (3)	01 Nov. 94 (3)	02 Nov. 94 (3)	22 Jul. 94 (5)	08 Nov. 94 (4)
14 Mar. 95 (3)	19 Oct. 94 (2)	06 Dec. 94 (4)	05 Dec. 94 (4)	22 Aug. 94 (3)	01 Dec. 94 (3)
28 Mar. 95 (2)	16 Nov. 94 (3)	04 Jan. 95 (4)	03 Jan. 95 (4)	23 Sep. 94 (4)	13 Jan. 95 (3)
11 Apr. 95 (3)	14 Dec. 94 (2)	09 Jan. 95 (1)	06 Feb. 95 (5)	31 Oct. 94 (3)	28 Feb. 95 (3)
25 Apr. 95 (2)	19 Jan. 95 (2)	07 Feb. 95 (4)	01 Mar. 95 (2)	15 Nov. 94 (4)	
21 Jun. 95 (2)	30 Mar. 95 (3)	15 Mar. 95 (3)	03 Apr. 95 (3)	09 Dec. 94 (2)	
	13 Apr. 95 (3)	06 Apr. 95 (3)	01 May 95 (4)	14 Dec. 94 (4)	
	27 Apr. 95 (3)	02 May 95 (3)	13 Jun. 95 (3)	23 Jan. 95 (2)	
	31 May 95 (3)	14 Jun. 95 (3)		17 Feb. 95 (2)	
	28 Jun. 95 (3)				

Note: The integers in parentheses identify the number of pavement evaluations that were performed on any given date. Multiple evaluations on the same date can provide information related to the effects of daily warming.

$$E = \frac{CV \cdot z}{\sqrt{n}} = \frac{6.4 \times 1.96}{\sqrt{1}} = 12.5\% \qquad (8)$$

These calculations are among those used to plot Figure B37.

A review of the figures in Appendix B reveals that the error associated with estimating mean deflection increased as drop height decreased and as the distance between load and sensor increased. These observations can be summarized as follows: percent error for deflection estimates increases as the magnitude of deflection decreases. The figures also show that error decreased as the number of replicates increased. This is a reflection of the improved confidence that accompanies larger sample sizes.

The following statements are based on further review of the data presented in Appendix B. The statements are generalized and include findings for all four drop heights and all six test sections.

Table 14
Statistics for Coefficients of Variation (%) Between Replicates of Normalized Deflection for Test Section 1002 in Massachusetts

Sensor Offset	Statistic	Target Load (kN) 26.7	40.0	53.4	71.2
0 mm	median	0.396	0.326	0.202	0.210
	skewness	3.27	2.48	2.94	2.55
	95th percentile	1.47	0.877	0.610	0.485
203 mm	median	0.461	0.370	0.217	0.231
	skewness	3.56	2.44	2.66	2.72
	95th percentile	1.31	0.821	0.605	0.533
305 mm	median	0.516	0.423	0.248	0.256
	skewness	2.80	2.24	2.84	3.04
	95th percentile	1.63	0.951	0.653	0.626
457 mm	median	0.580	0.482	0.295	0.262
	skewness	3.46	1.88	1.82	2.34
	95th percentile	1.63	1.08	0.723	0.652
610 mm	median	0.723	0.557	0.359	0.289
	skewness	3.88	1.72	1.74	2.34
	95th percentile	2.11	1.34	0.888	0.733
914 mm	median	1.02	0.729	0.504	0.388
	skewness	2.08	1.50	1.11	1.55
	95th percentile	2.81	1.63	1.19	0.939
1524 mm	median	2.50	1.52	1.11	0.883
	skewness	8.37	11.1	14.5	13.8
	95th percentile	6.40	4.08	2.68	2.08

Note: Data includes 990 sets of 4 replicates for each combination of target load and sensor offset.

a. Four replicates of deflection measurements at the center of the load plate provided a maximum error of 2.0 percent or less. Decreasing the number of replicates to two provided a maximum error of 2.5 percent or less.

b. At a sensor offset of 203 mm, four replicates of deflection measurements provided a maximum error of 2.5 percent or less. Decreasing the number of replicates to two provided a maximum error of 3.5 percent or less.

c. At a sensor offset of 305 mm, four replicates of deflection measurements provided a maximum error of 3.0 percent or less. Decreasing the number of replicates to two provided a maximum error of 4.0 percent or less.

d. At a sensor offset of 457 mm, four replicates of deflection measurements provided a maximum error of 4.0 percent or less. Decreasing the number of replicates to two provided a maximum error of 5.0 percent or less.

e. At a sensor offset of 610 mm, four replicates of deflection measurements provided a maximum error of 5.0 percent or less. Decreasing the number of replicates to two provided a maximum error of 7.0 percent or less.

Table 15
Statistics for Coefficients of Variation (%) Between Replicates of Normalized Deflection for Test Section 1002 in Vermont

Sensor Offset	Statistic	Target Load (kN) 26.7	40.0	53.4	71.2
0 mm	median	0.536	0.298	0.224	0.242
	skewness	5.73	5.81	5.52	5.72
	95th percentile	1.60	0.991	0.799	0.598
203 mm	median	0.547	0.309	0.240	0.254
	skewness	6.09	7.18	6.11	8.57
	95th percentile	1.64	0.931	0.751	0.689
305 mm	median	0.622	0.358	0.258	0.275
	skewness	5.91	7.31	7.97	5.50
	95th percentile	1.92	1.13	0.945	0.873
457 mm	median	0.733	0.434	0.313	0.318
	skewness	6.85	6.29	6.17	5.22
	95th percentile	2.29	1.37	1.06	1.18
610 mm	median	0.814	0.478	0.349	0.349
	skewness	15.2	16.1	17.3	18.0
	95th percentile	2.27	1.65	1.04	0.973
914 mm	median	1.12	0.698	0.507	0.454
	skewness	16.1	13.9	9.55	9.14
	95th percentile	3.15	2.30	1.75	1.57
1524 mm	median	2.07	1.33	0.972	0.771
	skewness	5.68	8.45	9.65	10.7
	95th percentile	6.75	4.57	3.58	2.99

Note: Data includes 1022 sets of 4 replicates for each combination of target load and sensor offset.

f. At a sensor offset of 914 mm, four replicates of deflection measurements provided a maximum error of 6.0 percent or less. Increasing the number of replicates to two provided a maximum error of 8.5 percent or less.

g. At a sensor offset of 1524 mm, four replicates of deflection measurements provided a maximum error of 8.5 percent or less. Decreasing the number of replicates to two provided a maximum error of 12 percent or less.

h. Generally, the highest variability between replicates was experienced at test section TX 1122 and the lowest variability between replicates was experienced at test section UT 1001. These different levels of repeatability are related to the stiffness of pavement response. The test section in Texas was shown previously to exhibit the smallest deflections, while the test section in Utah was shown to exhibit some of the largest deflections.

Table 16
Statistics for Coefficients of Variation (%) Between Replicates of Normalized Deflection for Test Section 1060 in Texas

Sensor Offset	Statistic	Target Load (kN)			
		26.7	40.0	53.4	71.2
0 mm	median	0.662	0.424	0.314	0.270
	skewness	1.48	1.50	1.36	3.19
	95th percentile	1.47	1.10	0.831	0.640
203 mm	median	0.726	0.485	0.350	0.302
	skewness	1.58	1.54	1.53	3.34
	95th percentile	1.65	1.20	0.950	0.795
305 mm	median	0.709	0.480	0.345	0.294
	skewness	2.39	1.61	1.63	3.07
	95th percentile	1.73	1.30	0.981	0.868
457 mm	median	0.775	0.542	0.402	0.337
	skewness	1.73	1.41	1.39	3.53
	95th percentile	1.91	1.46	1.10	0.984
610 mm	median	0.842	0.577	0.430	0.350
	skewness	1.51	1.44	1.86	2.77
	95th percentile	2.04	1.59	1.20	1.05
914 mm	median	1.06	0.764	0.567	0.458
	skewness	1.37	1.38	1.51	4.87
	95th percentile	2.62	1.98	1.48	1.28
1524 mm	median	1.55	1.12	0.835	0.669
	skewness	6.01	1.37	1.47	5.17
	95th percentile	3.82	2.89	2.25	2.04

Note: Data includes 1164 sets of 4 replicates for each combination of target load and sensor offset.

Table 17
Statistics for Coefficients of Variation (%) Between Replicates of Normalized Deflection for Test Section 1122 in Texas

Sensor Offset	Statistic	Target Load (kN) 26.7	40.0	53.4	71.2
0 mm	median	0.774	0.403	0.303	0.314
	skewness	2.00	1.89	1.83	1.80
	95th percentile	1.68	1.06	0.831	0.770
203 mm	median	1.09	0.668	0.505	0.424
	skewness	2.00	1.43	1.44	1.46
	95th percentile	2.29	1.70	1.30	1.03
305 mm	median	1.20	0.775	0.566	0.475
	skewness	1.79	1.49	1.28	2.14
	95th percentile	2.87	2.17	1.63	1.27
457 mm	median	1.51	1.07	0.755	0.627
	skewness	1.89	1.25	1.14	1.09
	95th percentile	3.58	2.67	2.11	1.70
610 mm	median	1.86	1.24	0.938	0.742
	skewness	1.80	1.14	1.16	0.904
	95th percentile	4.73	3.50	2.67	1.97
914 mm	median	2.58	1.78	1.28	0.988
	skewness	2.00	1.01	1.12	1.19
	95th percentile	5.93	4.56	3.35	2.68
1524 mm	median	4.00	2.82	2.02	1.56
	skewness	1.69	1.62	0.725	1.31
	95th percentile	8.47	6.50	5.00	3.99

Note: Data includes 1396 sets of 4 replicates for each combination of target load and sensor offset.

Table 18
Statistics for Coefficients of Variation (%) Between Replicates of Normalized Deflection for Test Section 8129 in Montana

Sensor Offset	Statistic	Target Load (kN)			
		26.7	40.0	53.4	71.2
0 mm	median	0.617	0.268	0.210	0.240
	skewness	2.45	4.67	2.96	2.54
	95th percentile	1.78	0.966	0.702	0.654
203 mm	median	0.569	0.261	0.245	0.291
	skewness	9.08	12.5	5.26	9.55
	95th percentile	1.88	1.27	0.886	0.737
305 mm	median	0.539	0.286	0.276	0.313
	skewness	3.72	17.0	2.48	4.16
	95th percentile	1.83	1.20	0.846	0.714
457 mm	median	0.535	0.333	0.307	0.354
	skewness	4.29	15.8	3.15	5.58
	95th percentile	1.84	1.33	0.925	0.757
610 mm	median	0.559	0.403	0.347	0.409
	skewness	11.9	16.8	17.2	16.2
	95th percentile	1.91	1.53	1.11	0.857
914 mm	median	0.646	0.519	0.407	0.446
	skewness	2.84	17.9	2.98	3.15
	95th percentile	2.07	1.75	1.13	0.953
1524 mm	median	0.882	0.725	0.516	0.500
	skewness	2.37	36.4	2.28	4.90
	95th percentile	2.87	2.17	1.36	1.24

Note: Data includes 1418 sets of 4 replicates for each combination of target load and sensor offset.

Table 19
Statistics for Coefficients of Variation (%) Between Replicates of Normalized Deflection for Test Section 1001 in Utah

Sensor Offset	Statistic	Target Load (kN) 26.7	40.0	53.4	71.2
0 mm	median	0.395	0.230	0.191	0.210
	skewness	1.14	1.71	3.00	15.4
	95th percentile	0.797	0.509	0.467	0.495
203 mm	median	0.394	0.253	0.211	0.212
	skewness	20.4	18.0	18.8	9.50
	95th percentile	0.811	0.553	0.506	0.513
305 mm	median	0.394	0.257	0.217	0.202
	skewness	1.00	1.29	1.47	1.40
	95th percentile	0.802	0.543	0.494	0.476
457 mm	median	0.435	0.283	0.242	0.215
	skewness	1.02	1.56	1.39	3.89
	95th percentile	0.910	0.650	0.552	0.519
610 mm	median	0.454	0.314	0.275	0.250
	skewness	2.43	1.70	1.73	1.73
	95th percentile	1.08	0.739	0.656	0.583
914 mm	median	0.574	0.386	0.354	0.321
	skewness	2.76	1.86	1.43	1.61
	95th percentile	1.38	0.969	0.793	0.740
1524 mm	median	0.870	0.604	0.517	0.480
	skewness	4.25	3.09	3.77	3.68
	95th percentile	2.55	1.83	1.38	1.34

Note: Data includes 980 sets of 4 replicates for each combination of target load and sensor offset.

Falling-Weight Deflectometer Station-Spacing Study

Interpretation of Test Results

Data from FWD tests can be reduced by many different methods. The most common method involves the back-calculation of an elastic modulus for each pavement layer. Other methods include dynamic analyses and the inspection of deflection basin curvature. In this project, when beginning the study of spatial variability in pavements, the type of FWD analysis was expected to influence conclusions. Therefore, analysis methods included the calculation of modulus values and the modeling of pavements as dynamic systems involving a mass, a spring, and a dashpot. Conclusions concerning spatial variability were not found to be substantially dependent on the type of analysis. Therefore, a relatively simple FWD analysis parameter was selected for implementation. This parameter, called the impulse stiffness modulus (ISM), is commonly used by government agencies during pavement evaluations. The ISM is defined as:

$$\mathrm{ISM} = \frac{\text{peak load}}{\text{peak deflection}} \tag{9}$$

Calculated ISM values for the test sections are presented in Appendix C. In these figures, each plotted ISM value represents the average ISM for the nine test stations during a single pavement evaluation. ISM was calculated separately for the different target loads and test paths (midlane and outside wheelpath). Inspection of the figures in Appendix C reveals that the pavements were stiffest during winter months. The pavements in Massachusetts, Vermont, and Montana experienced 3- to 10-fold increases in ISM values during winter months. ISM measurements for each test section are also summarized in Table 20 with median and 90 percent confidence interval statistics. Using median ISM values, the following ranking of test sections is in order of increasing structural stiffness: MT 8129, UT 1001, MA 1002, VT 1002, TX 1060, TX 1122.

Variability among stations for FWD test results was quantified for each of the six test sections. Variability results for each target load and for each test path (midlane and outside wheelpath) were calculated separately. The collected data provided 56 to 134 estimates for coefficient of variation for each test path/ target load combination. All the calculated coefficients of variation are plotted

Table 20
Median and (90 Percent Confidence Interval) for all Measured Impulse Stiffness Moduli

Test Section	Test Path	No. of FWD Tests[a]	Target Load (kN) 26.7	40.0	53.4	71.2
MA 1002	1	648	195 (133-280)	199 (139-280)	203 (145-286)	208 (151-294)
	3	639	185 (125-276)	190 (132-279)	194 (138-282)	200 (146-290)
VT 1002	1	504	215 (128-726)	215 (135-728)	218 (139-720)	218 (143-713)
	3	504	213 (118-684)	212 (124-688)	210 (128-681)	214 (132-670)
TX 1060	1	738	288 (214-366)	290 (216-364)	292 (214-362)	294 (217-362)
	3	729	278 (174-379)	279 (176-373)	279 (177-369)	282 (180-368)
TX 1122	1	837	359 (270-454)	349 (267-429)	347 (270-418)	345 (268-411)
	3	837	328 (253-457)	322 (255-430)	324 (260-420)	326 (263-412)
MT 8129	1	1170	73.7 (57.6-858)	77.5 (61.5-883)	81.2 (64.7-905)	85.4 (67.9-924)
	3	1206	67.4 (50.8-824)	71.7 (54.9-834)	76.2 (59.3-865)	80.3 (67.1-885)
UT 1001	1	900	118 (76.9-180)	117 (76.2-176)	116 (75.9-173)	122 (79.5-179)
	3	855	97.4 (62.7-135)	97.4 (64.0-136)	98.7 (66.7-138)	103 (70.9-143)

[a] For each drop height.
Note: Each FWD test, at each drop height, represented the average of four replicates.

in the figures shown in Appendix D. The figures are organized by test section and test path. Median and maximum values for the coefficients of variation among stations are also presented in Table 21.

As would be expected, the variabilities between stations were higher than those between replicates. The two test paths within each test section exhibited similar variabilities. The variability between stations tended to decrease slightly as the target load (drop height) increased. Median variability was generally higher for test sections TX 1060, TX 1122, and UT 1001, relative to the variability for test sections MA 1002, VT 1002, and MT 8129. The test sections with the highest median variabilities were located in the hottest climates. Inspection of the figures in Appendix C also reveals that variability among stations increased substantially during winter months for test sections MA 1002, VT 1002, and MT 8129.

Table 21
Median (and Maximum Value) for Coefficients of Variation (%) Among Stations

Test Section	Test Path	Data Count[a]	Target Load (kN) 26.7	40.0	53.4	71.2
MA 1002	1	72	7.77 (34.2)	7.00 (30.6)	6.48 (27.1)	6.24 (26.3)
	3	71	8.97 (25.6)	7.96 (25.3)	7.22 (24.5)	6.86 (24.3)
VT 1002	1	56	8.63 (17.1)	8.84 (13.6)	8.74 (14.3)	8.98 (12.7)
	3	56	7.96 (13.1)	7.77 (11.7)	7.99 (11.8)	7.75 (11.4)
TX 1060	1	82	12.0 (15.2)	12.3 (15.3)	12.0 (15.0)	11.8 (14.9)
	3	81	19.5 (29.3)	19.3 (28.6)	19.3 (28.2)	19.4 (27.8)
TX 1122	1	93	13.4 (16.8)	12.8 (15.6)	12.2 (14.4)	11.9 (13.7)
	3	93	16.3 (22.1)	15.3 (20.7)	14.3 (19.1)	13.7 (18.5)
MT 8129	1	130	4.89 (26.8)	4.80 (23.0)	4.78 (21.4)	4.55 (19.4)
	3	134	7.00 (38.8)	6.59 (21.9)	6.20 (14.5)	5.34 (13.6)
UT 1001	1	100	19.3 (28.8)	18.6 (27.7)	18.3 (26.9)	18.4 (26.6)
	3	95	14.8 (19.9)	14.8 (20.3)	15.0 (20.3)	15.1 (19.8)

[a] Number of available estimates for coefficient of variation.
Note: Each estimate for coefficient of variation included nine FWD test locations.

Comparison of Information Using Different Station Spacings

Having summarized the ISM response of pavements and variability characteristics, recall that the goal of this portion of the study is to optimize the distance between test stations. Relatively large station spacings would result in less costly pavement evaluation procedures. However, relatively large station spacings may not be desirable if valuable technical information could be attained with closer station spacings. In order to facilitate this decision process, this section compares important statistical information acquired from FWD tests, using different station spacings. This section investigates the quality of information would be obtained if station spacings of 15.2 m (50 ft) or 30.5 m (100 ft) had been used, rather than a station spacing of 7.6 m (25 ft). The larger station spacings of 15.2 m and 30.5 m were chosen because they are multiples of the smaller station spacing of 7.6 m (25 ft).

The statistics calculated for the ISM response for each station spacing included mean, standard deviation, minimum, and maximum. These statistics were calculated for each set of FWD tests, where each set included nine test stations. Results are presented as percent error for the larger station spacings (15.2 m and 30.5 m), relative to the most detailed information available, which was obtained with a station spacing of 7.6 m. In order to keep the errors in perspective with the mean measurements, they were calculated as shown below. In order to improve clarity, the equations are presented in terms of lag numbers, rather than station spacings. Lag numbers of 1, 2, and 4 correspond to station spacings of 7.6 m, 15.2 m, and 30.5 m, respectively.

$$\text{Percent Error for Mean for Lag Number } i = \frac{\bar{x}_i - \bar{x}_1}{\bar{x}_1} \times 100\% \quad (10)$$

where

$\bar{x}_i$ = calculated mean for lag 2 or 4

$\bar{x}_1$ = calculated mean for lag 1

Percent Error for Standard Deviation for Lag

$$\text{Number } i = \frac{\bar{s}_i - \bar{s}_1}{\bar{x}_1} \times 100\% \quad (11)$$

where

$\bar{s}_i$ = calculated standard deviation for lag 2 or 4

$\bar{s}_1$ = calculated standard deviation for lag 1

$\bar{x}_1$ = calculated mean for lag 1

Percent Error for Minimum for Lag

$$\text{Number } i = \frac{\min_i - \min_1}{\bar{x}_1} \times 100\% \quad (12)$$

where

$\min_i$ = calculated minimum for lag 2 or 4

$\min_1$ = calculated minimum for lag 1

$\bar{x}_1$ = calculated mean for lag 1

Percent Error for Maximum for Lag

$$\text{Number } i = \frac{\max_i - \max_1}{\bar{x}_1} \times 100\% \quad (13)$$

where

$\max_i$ = calculated maximum for lag 2 or 4

$\max_1$ = calculated maximum for lag 1

$\bar{x}_1$ = calculated mean for lag 1

Errors associated with ISM mean, standard deviation, minimum, and maximum are shown in Appendix E (in the same order). The figures for each statistic are organized by test section and then by station spacing. When station spacing was increased to either 15.2 m or 30.5 m, errors in estimating test section mean response were generally less than 5 percent. However, test section UT 1001 had larger errors, most of which were less than 10 percent. Also, during winter months in Massachusetts and Montana, errors were as high as approximately 10 percent.

When station spacing was increased to 15.2 m, errors in estimating test section variability (standard deviation) were also generally less than 5 percent. When station spacing was increased to 30.5 m, errors in estimating standard deviation were generally less than 10 percent, although test sections TX 1060 and UT 1001 had errors as high as 15 percent.

When station spacing was increased to either 15.2 m or 30.5 m, errors in estimating test section minimum ISM were generally less than 20 percent and errors in estimating test section maximum ISM were generally less than 15 percent. However, at a station spacing of 30.5 m, errors in estimating maximum ISM for the outside wheelpath of UT 1001 ranged primarily from 20 to 35 percent.

Calculated errors are also summarized in Tables 22 through 27. Each table summarizes the errors for a single project. For each of ISM mean, standard deviation, minimum, and maximum, the following statistics are provided for the distribution of calculated errors: median, skew, 5th percentile, and 95th percentile. The range of errors defined by the 5th and 95th percentiles generally support the previous statements that were based on observations from the figures in Appendix E.

The authors investigated the possibility of a correlation between the magnitude of errors associated with characterizing test section ISM response and the overall test section variability (coefficient of variation). The premise was that highly variable test sections would be prone to large errors with increases in station spacing. This relationship was established for the case of estimating standard deviation with a station spacing of 30.5 m (100 ft), as shown in Figure 3. The coefficient of determination (R^2) for this relationship was 0.72. However, this relationship was weak when station spacing was only increased to 15.2 m (50 ft); the coefficient of determination in this case was 0.3. Linear relationships between the magnitude of errors and overall test section variability did not exist for the estimates of mean, minimum, or maximum ISM; coefficients of determination in these cases ranged from 0.0 to 0.2.

Table 22
Distribution Statistics for the Percentages of Error in ISM Calculations Caused by Increasing Station Spacing at Test Section MA 1002

ISM Calculation for the Test Section	Test Path	Station Spacing	Statistic[a] for the Distribution of Error			
			Median	Skew	P(5)	P(95)
Mean	1	15.2 m	0.12	-1.4	-1.7	1.7
		30.5 m	-1.4	-2.2	-4.2	1.7
	3	15.2 m	2.7	-1.3	1.4	4.8
		30.5 m	.072	-3.0	-5.3	2.8
Standard Deviation	1	15.2 m	-0.23	-0.15	-2.0	1.0
		30.5 m	0.90	0.85	-1.8	4.2
	3	15.2 m	-1.3	-1.3	-4.9	0.18
		30.5 m	-1.7	-1.2	-6.9	0.36
Minimum	1	15.2 m	0.85	2.5	0.0	6.5
		30.5 m	0.85	2.4	0.0	6.5
	3	15.2 m	10	1.3	4.1	24
		30.5 m	10	1.3	4.1	24
Maximum	1	15.2 m	0.0	-1.4	-5.6	0.0
		30.5 m	-3.5	0.05	-6.8	0.0
	3	15.2 m	0.0	-6.3	-1.7	0.0
		30.5 m	-3.8	-1.2	-16	0.0

[a] P(5) = 5th percentile; P(95) = 95th percentile
Note: Percent error estimates for test paths 1 and 3 were obtained for 288 and 284 sets of data, respectively. Each data set included 9 FWD test stations.

Table 23
Distribution Statistics for the Percentages of Error in ISM Calculations Caused by Increasing Station Spacing at Test Section VT 1002

ISM Calculation for the Test Section	Test Path	Station Spacing	Statistic[a] for the Distribution of Error			
			Median	Skew	P(5)	P(95)
Mean	1	15.2 m	0.63	-2.3	-0.50	1.6
		30.5 m	2.0	-3.1	-1.3	3.8
	3	15.2 m	2.0	-0.25	0.20	3.4
		30.5 m	3.1	-1.6	-0.78	6.5
Standard Deviation	1	15.2 m	2.6	-3.0	1.7	3.1
		30.5 m	6.6	-10	2.1	7.9
	3	15.2 m	1.6	-1.5	0.10	2.5
		30.5 m	3.8	-1.2	-0.42	5.8
Minimum	1	15.2 m	0.0	7.7	0.0	0.0
		30.5 m	0.0	13	0.0	0.0
	3	15.2 m	0.0	2.5	0.0	4.1
		30.5 m	0.0	2.7	0.0	7.6
Maximum	1	15.2 m	0.0	-8.7	0.0	0.0
		30.5 m	0.0	-13	-0.90	0.0
	3	15.2 m	0.0	-5.2	0.0	0.0
		30.5 m	0.0	-6.5	-1.7	0.0

[a] P(5) = 5th percentile; P(95) = 95th percentile
Note: Percent error estimates for test paths 1 and 3 were obtained for 224 sets of data. Each data set included 9 FWD test stations.

Table 24
Distribution Statistics for the Percentages of Error in ISM Calculations Caused by Increasing Station Spacing at Test Section TX 1060

ISM Calculation for the Test Section	Test Path	Station Spacing	Statistic[a] for the Distribution of Error			
			Median	Skew	P(5)	P(95)
Mean	1	15.2 m	-0.37	-17	-1.5	0.72
		30.5 m	2.3	-10	-0.64	4.5
	3	15.2 m	-0.01	-0.44	-1.6	1.1
		30.5 m	-1.0	-0.23	-5.1	2.4
Standard Deviation	1	15.2 m	2.5	16	1.8	3.4
		30.5 m	4.2	3.9	0.88	7.0
	3	15.2 m	2.2	0.47	0.60	4.9
		30.5 m	5.8	0.43	0.56	13
Minimum	1	15.2 m	0.0	18	0.0	0.0
		30.5 m	1.5	0.95	0.0	9.0
	3	15.2 m	0.0	2.2	0.0	4.5
		30.5 m	0.0	2.4	0.0	5.3
Maximum	1	15.2 m	0.0	-4.5	-2.0	0.0
		30.5 m	0.0	-4.5	-2.0	0.0
	3	15.2 m	0.0	-2.7	-2.8	0.0
		30.5 m	-1.3	-1.4	-6.8	0.0

[a] P(5) = 5th percentile; P(95) = 95th percentile
Note: Percent error estimates for test paths 1 and 3 were obtained for 328 and 324 sets of data, respectively. Each data set included 9 FWD test stations.

Table 25
Distribution Statistics for the Percentages of Error in ISM Calculations Caused by Increasing Station Spacing at Test Section TX 1122

ISM Calculation for the Test Section	Test Path	Station Spacing	Statistic[a] for the Distribution of Error			
			Median	Skew	P(5)	P(95)
Mean	1	15.2 m	-1.5	-16	-2.7	-0.10
		30.5 m	-1.1	-10	-3.3	1.3
	3	15.2 m	0.15	-0.03	-1.5	2.1
		30.5 m	-0.90	-0.14	-4.7	2.0
Standard Deviation	1	15.2 m	-2.1	5.9	-4.6	0.03
		30.5 m	-0.87	2.7	-4.2	2.9
	3	15.2 m	-0.94	0.10	-3.6	2.0
		30.5 m	4.0	0.04	-0.39	9.4
Minimum	1	15.2 m	8.8	0.08	2.0	16
		30.5 m	10	0.23	5.3	17
	3	15.2 m	5.9	0.17	0.0	9.6
		30.5 m	5.9	0.17	0.0	9.6
Maximum	1	15.2 m	-3.3	-0.84	-11	0.0
		30.5 m	-3.5	-0.82	-11	0.0
	3	15.2 m	0.0	-1.9	-8.0	0.0
		30.5 m	0.0	-2.2	-8.5	0.0

[a] P(5) = 5th percentile; P(95) = 95th percentile
Note: Percent error estimates for test paths 1 and 3 were obtained for 372 and 372 sets of data, respectively. Each data set included 9 FWD test stations.

Table 26
Distribution Statistics for the Percentages of Error in ISM Calculations Caused by Increasing Station Spacing at Test Section MT 8129

ISM Calculation for the Test Section	Test Path	Station Spacing	Statistic[a] for the Distribution of Error			
			Median	Skew	P(5)	P(95)
Mean	1	15.2 m	-0.01	2.3	-0.92	2.0
		30.5 m	-1.4	2.9	-3.0	2.4
	3	15.2 m	1.3	2.9	0.23	3.3
		30.5 m	1.4	4.4	-1.1	6.5
Standard Deviation	1	15.2 m	-0.55	-0.39	-2.6	0.84
		30.5 m	-0.70	2.0	-3.4	2.8
	3	15.2 m	-1.6	-0.57	-3.8	1.2
		30.5 m	-1.8	0.32	-6.8	2.5
Minimum	1	15.2 m	1.2	2.1	0.0	8.8
		30.5 m	1.2	2.5	0.0	9.0
	3	15.2 m	6.8	0.10	0.31	12
		30.5 m	8.6	0.37	0.62	17
Maximum	1	15.2 m	-1.3	-0.93	-5.1	0.0
		30.5 m	-3.9	-0.25	-9.0	0.0
	3	15.2 m	-0.71	-7.6	-6.8	0.0
		30.5 m	-2.6	-4.1	-9.6	0.0

[a] P(5) = 5th percentile; P(95) = 95th percentile
Note: Percent error estimates for test paths 1 and 3 were obtained for 520 and 536 sets of data, respectively. Each data set included 9 FWD test stations.

Table 27
Distribution Statistics for the Percentages of Error in ISM Calculations Caused by Increasing Station Spacing at Test Section UT 1001

ISM Calculation for the Test Section	Test Path	Station Spacing	Statistic[a] for the Distribution of Error			
			Median	Skew	P(5)	P(95)
Mean	1	15.2 m	7.6	0.29	5.4	10
		30.5 m	7.4	-0.04	3.1	11
	3	15.2 m	0.86	0.67	-0.04	2.5
		30.5 m	-4.7	0.61	-6.5	-2.1
Standard Deviation	1	15.2 m	2.0	0.38	0.25	4.2
		30.5 m	8.0	-0.31	1.4	14
	3	15.2 m	-1.0	0.47	-3.5	2.9
		30.5 m	-10	0.11	-14	-7.5
Minimum	1	15.2 m	11	-0.78	0.61	15
		30.5 m	11	-0.79	0.61	15
	3	15.2 m	11	-0.75	2.0	16
		30.5 m	12	-0.64	3.8	16
Maximum	1	15.2 m	0.0	0.0	0.0	0.0
		30.5 m	0.0	0.0	-9.2	0.0
	3	15.2 m	0.0	-1.3	-7.3	0.0
		30.5 m	-27	-0.50	-34	-22

[a] P(5) = 5th percentile; P(95) = 95th percentile.
Note: Percent error estimates for test paths 1 and 3 were obtained for 400 and 380 sets of data, respectively. Each data set included 9 FWD test stations.

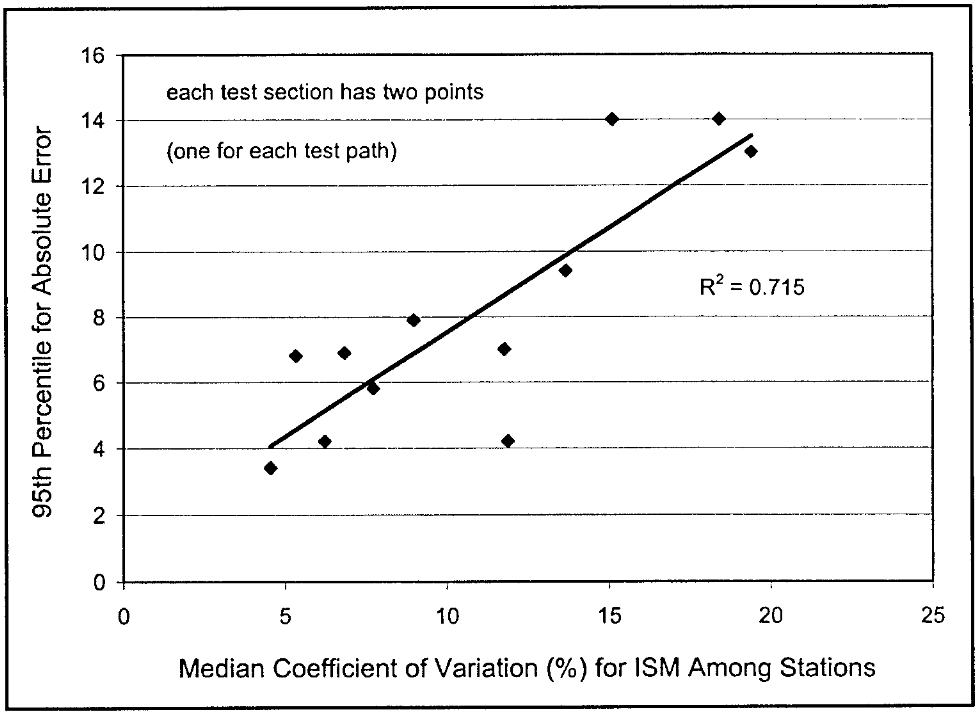

Figure 3. Relationship between test section variability and error associated with estimating the standard deviation

Summary and Conclusions

The following conclusions and recommendations are based on observations from the six test sections included in this study. All the test sections in this study were surfaced with asphalt concrete. The test sections were selected in a manner to represent a range of climatic conditions and a range of structural characteristics.

Replicate Study

The variability between replicate FWD drops was relatively low. Almost all coefficients of variation between replicates were less than 10 percent and most were less than 5 percent. The level of variability was related to the magnitude of measured deflections. For example, variability between replicates increased with increases in pavement stiffness, which were a function of the structure and the climate. Test section TX 1122, which responded to FWD testing with the highest stiffness, exhibited the highest variability between replicates. Test sections in colder climates exhibited increases in variability between replicates during winter months. Sensor offset from load and drop height also affected the magnitude of measured deflections and therefore influenced replicate variability. As sensor offset increased and as drop height decreased, measured deflections became smaller and the variability between replicates became larger.

When using four replicate drops for the lowest drop height, the maximum expected error for deflection calculations ranged from 2.0 to 8.5 percent, depending on the sensor location. These data include results from all the test sections. The lowest drop height is used here because it promotes the highest variability. If only two replicate drops were used, the maximum expected error for deflection calculations would range from 2.5 to 12 percent, depending on the sensor location. Due to these small changes in expected error, a reduction in replicate drops for FWD testing appears to be reasonable and without substantial loss in precision.

Station-Spacing Study

The variability among FWD test stations, within each test section, was higher than the variability between replicate drops. Median variabilities among stations for the various test sections ranged from 5 percent to 20 percent. Maximum variabilities encountered on specific dates approached 30 percent in some cases. The two test sections in Texas and the test section in Utah exhibited the highest variabilities between stations. These test sections did not have any unique structural characteristics, however, they happened to have been located in the hottest climates. Considering that the variabilities among stations at these sites were not extraordinarily large during summer months, the reason for their higher variabilities is most likely not related to temperature. It is most likely related to construction procedures and/or the uniformity of the subgrade along the test section.

Considering the data obtained for all test sections, an increase in station spacing from 7.6 m (25 ft) to 15.2 m (50 ft) would have resulted in the following approximate errors for estimates of test section ISM characteristics: up to a 10 percent error in mean value, up to a 5 percent error in standard deviation, up to a 25 percent error in minimum value, and up to a 10 percent error in maximum value. An increase in station spacing from 7.6 m (25 ft) to 30.5 m (100 ft) would have resulted in the following approximate errors: up to a 10 percent error in mean value, up to a 15 percent error in standard deviation, up to a 25 percent error in minimum value, and up to a 35 percent error in maximum value.

Predicting how large these errors would be for a particular test section, not included in this study, would be difficult. Little correlation was found between the magnitude of errors and the overall variability of test sections.

The decision as to whether station spacing can be increased without substantial loss of information depends on the manner by which test sections will be characterized. If test sections will be characterized as a single entity with a mean and standard deviation, an increase in station spacing from 7.6 m to 15.2 m appears to be reasonable. If the weakest or strongest response to FWD testing was viewed as the most crucial information related to test section performance, however, an increase in station spacing would be less desirable. When considering extremes in the response of a test section to load over its length, an increase in station spacing from 7.6 m to 15.2 m results in a substantial loss of information.

Applicability of Results to Other LTPP Sites

The test sections in this study were all surfaced with asphalt concrete and were all selected from the Seasonal Monitoring Program (SMP). The current FWD test procedures for these sites involve testing 61.0 m (200 ft) of the 152 m (500 ft) test sections, with a station spacing of 7.6 m (25 ft). The current FWD test procedures for non-SMP test sections in both the General Pavement Study (GPS) and the Specific Pavement Study (SPS) involve testing the full 152 m length, with a station spacing of 15.2 m (50 ft). The FWD procedures followed at each test station, however, are identical for the SMP sites and the non-SMP sites.

Considering these similarities and differences between LTPP sites, the recommendations presented in this report for test replicates should be directly applicable to other asphalt concrete pavements in the GPS and SPS, including non-SMP test sections. When considering increasing the station spacing at non-SMP sites, however, the recommendations presented in this report are not directly applicable. The methods of analysis demonstrated in this study should be applied directly to data obtained from the non-SMP test sections.

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Appendix A
Air and Pavement Surface Temperatures

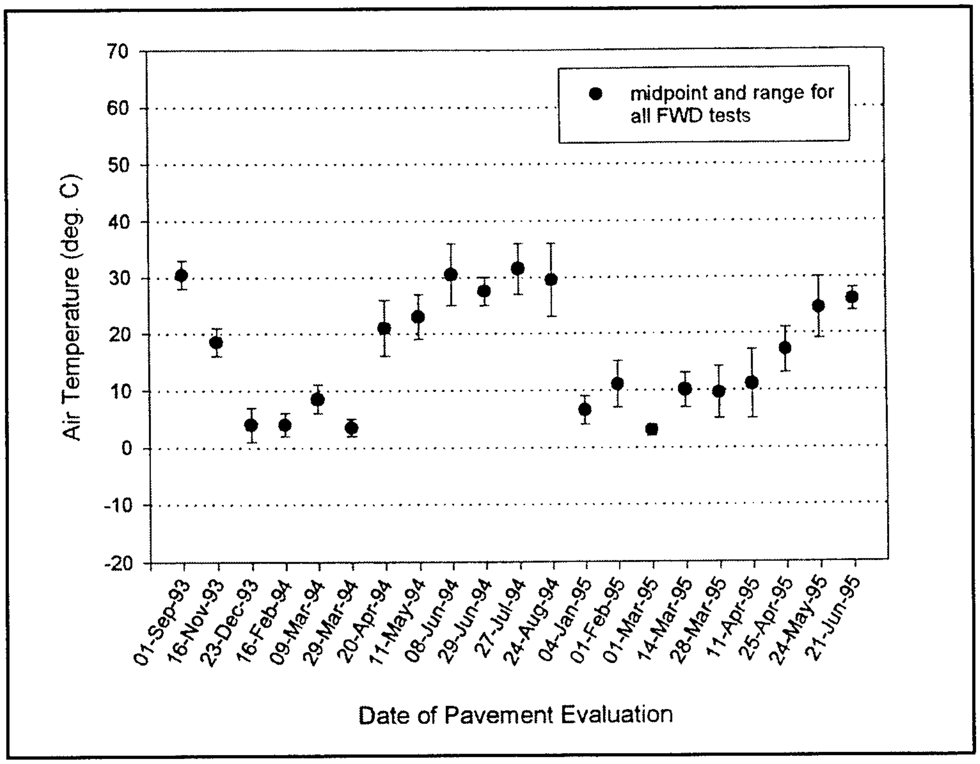


Figure A1. Air temperature measurements for test section 1002 in Massachusetts

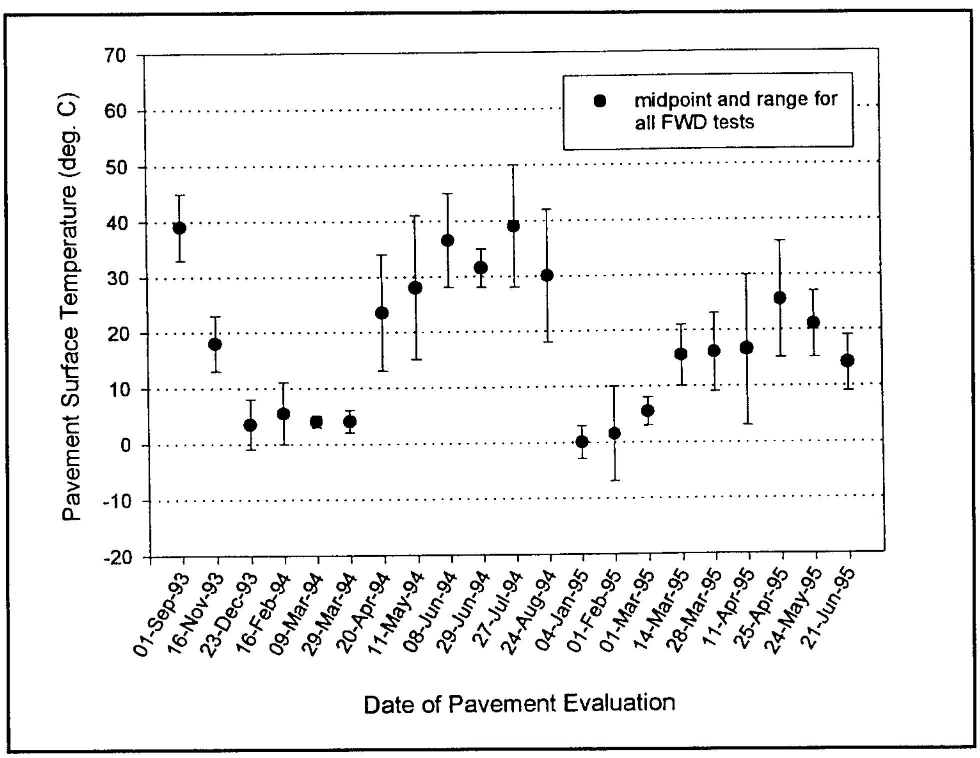


Figure A2. Pavement surface temperature measurements for test section 1002 in Massachusetts

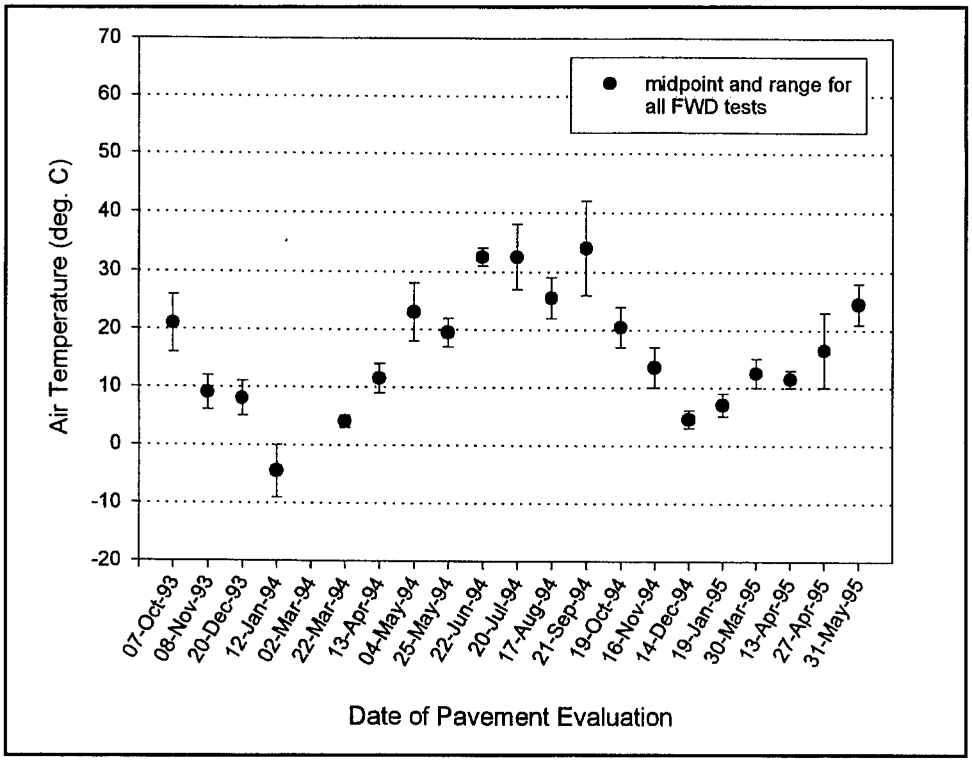


Figure A3. Air temperature measurements for test section 1002 in Vermont

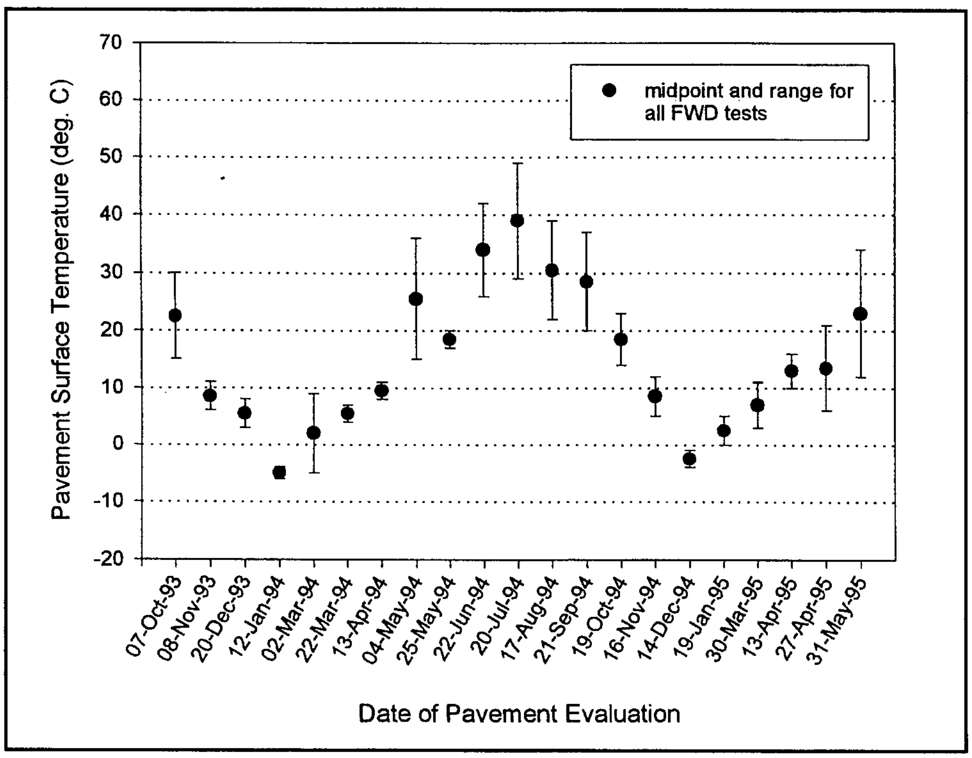


Figure A4. Pavement surface temperature measurements for test section 1002 in Vermont

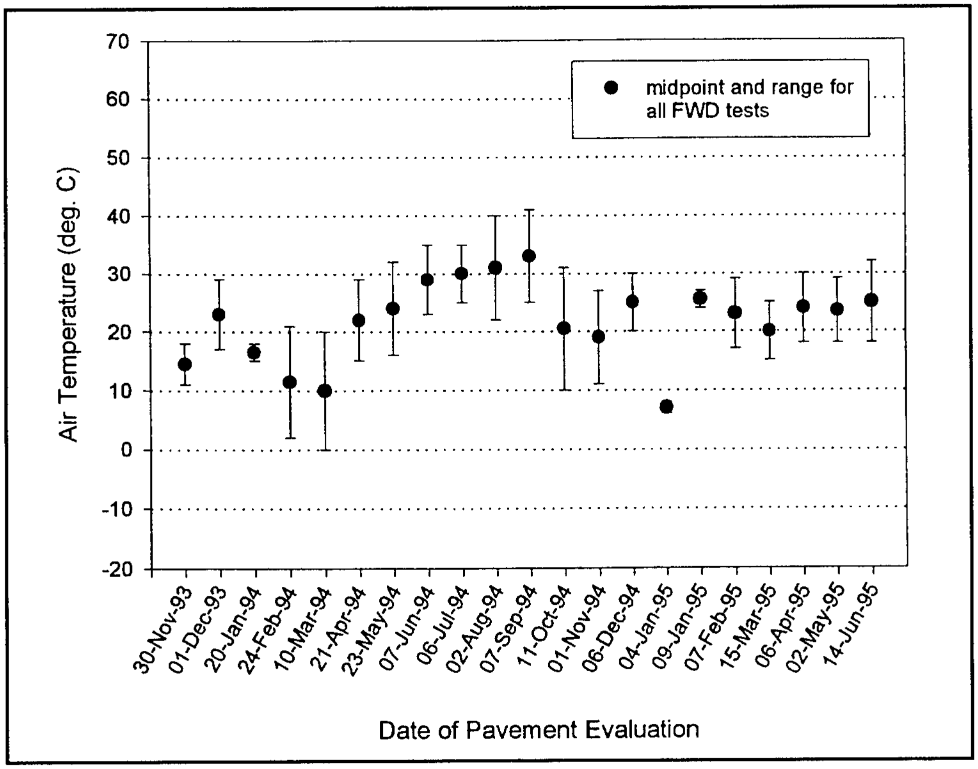


Figure A5. Air temperature measurements for test section 1060 in Texas

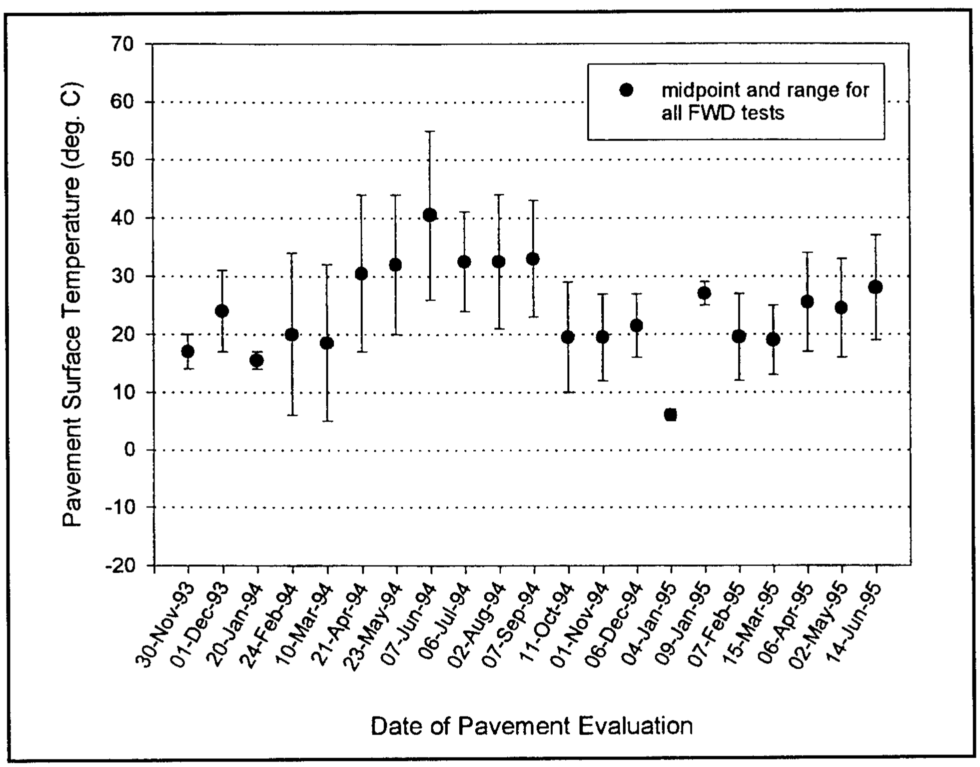


Figure A6. Pavement surface temperature measurements for test section 1060 in Texas

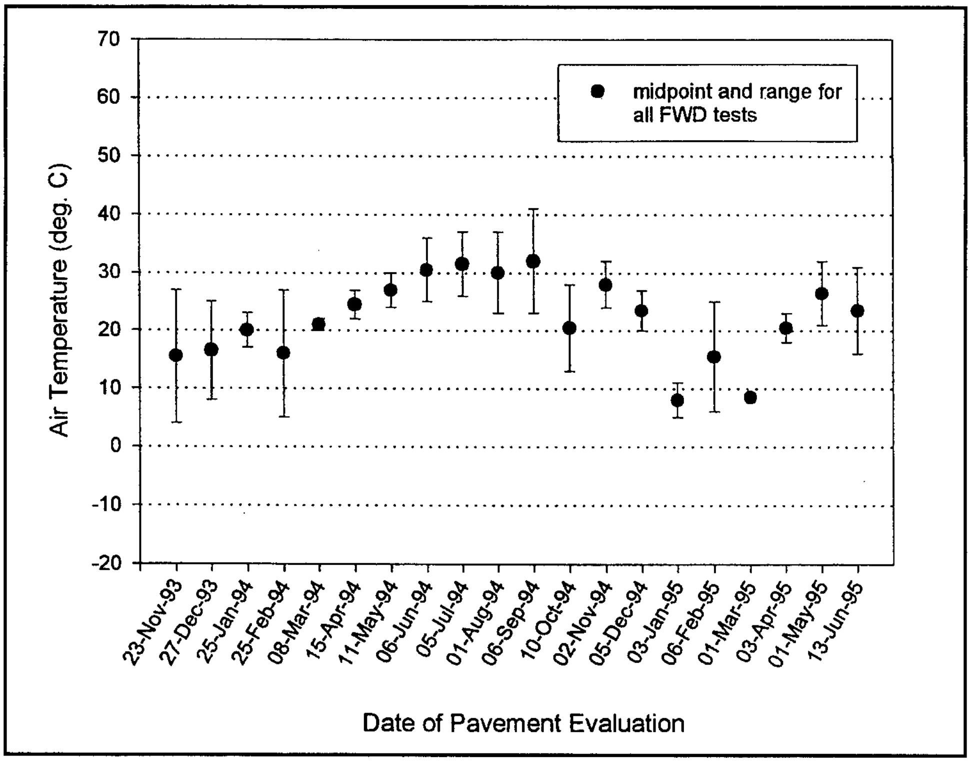


Figure A7. Air temperature measurements for test section 1122 in Texas

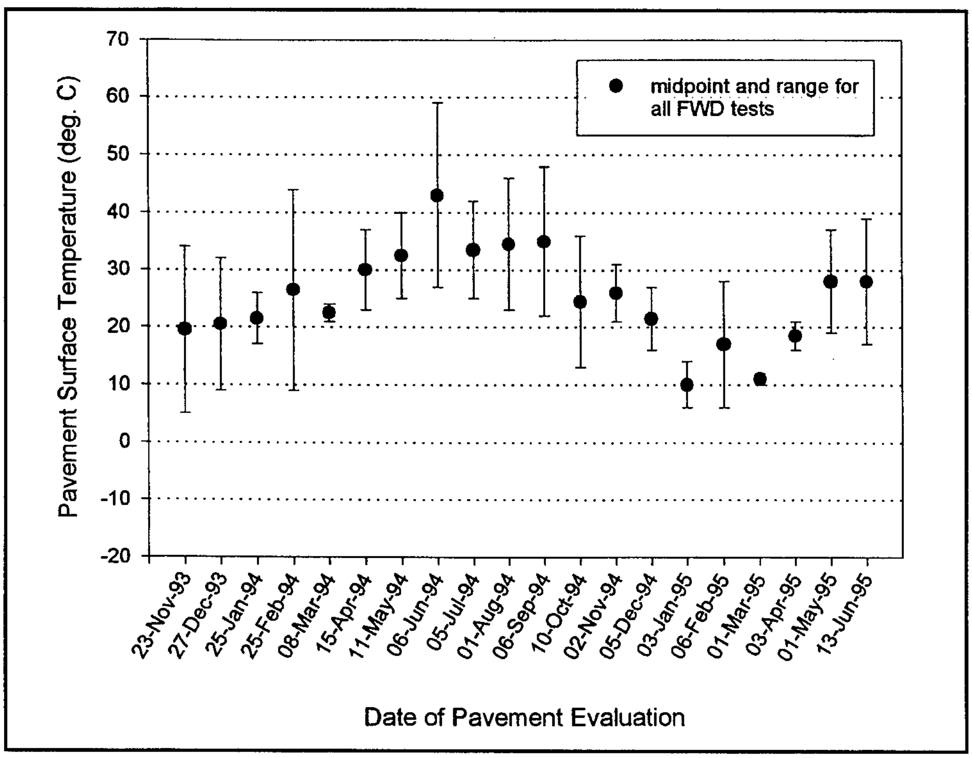


Figure A8. Pavement surface temperature measurements for test section 1122 in Texas

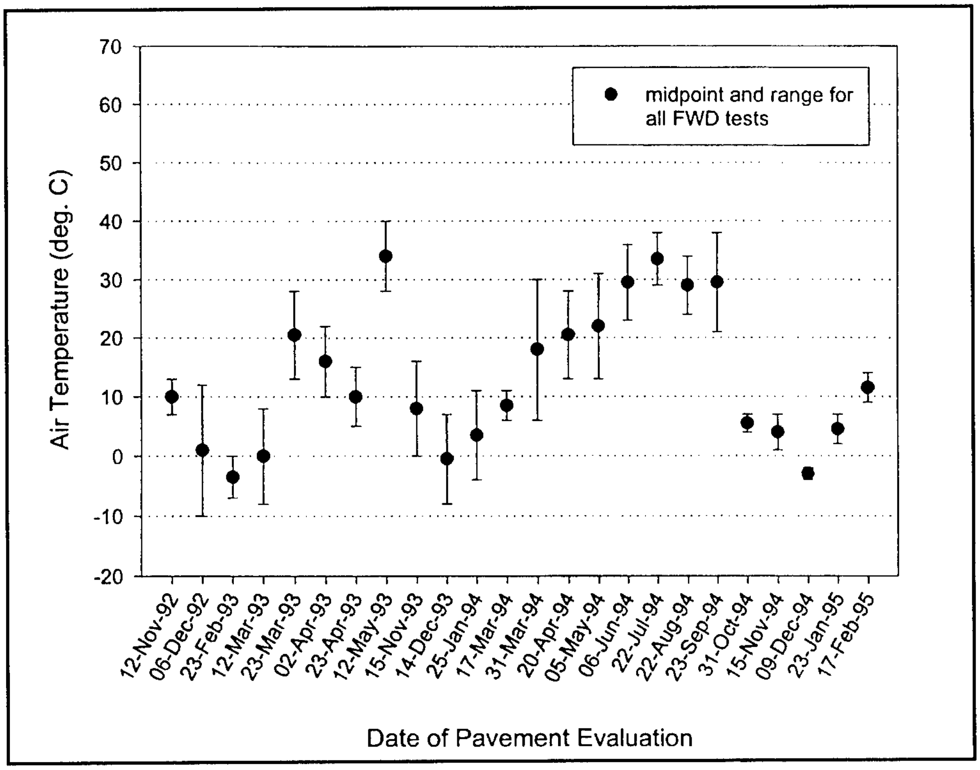


Figure A9. Air temperature measurements for test section 8129 in Montana

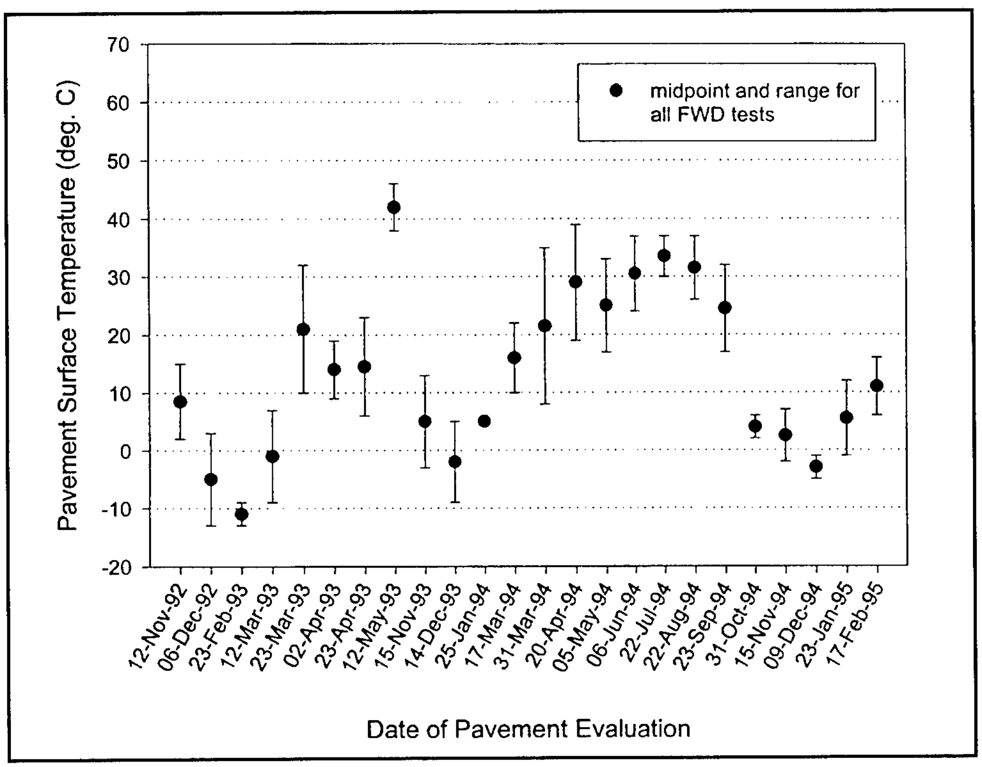


Figure A10. Pavement surface temperature measurements for test section 8129 in Montana

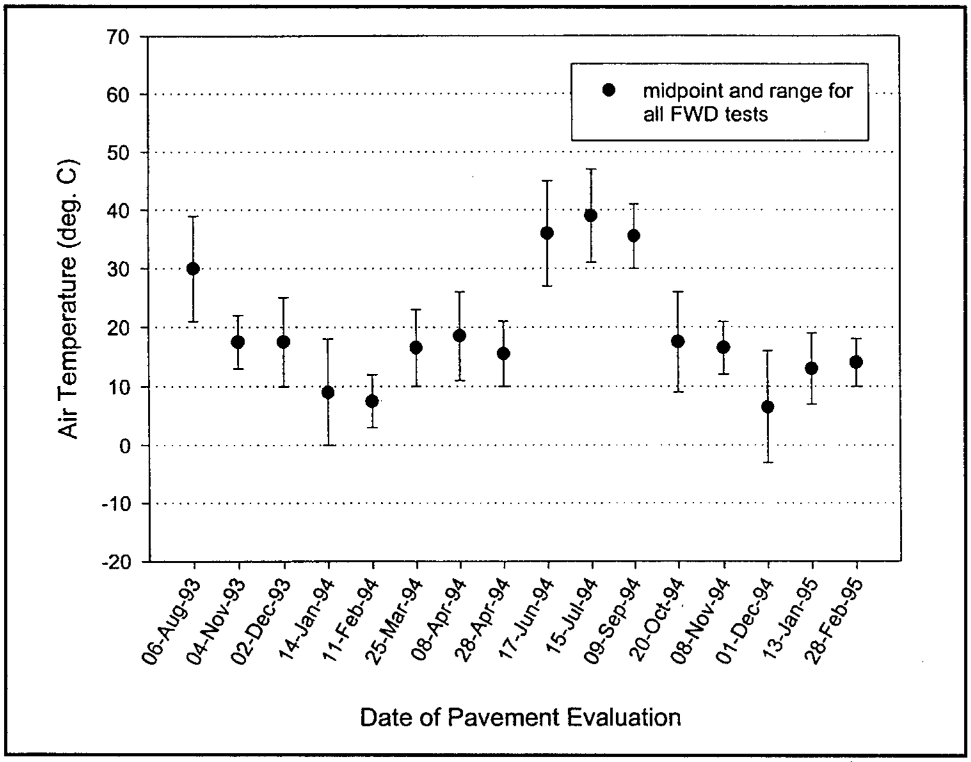


Figure A11. Air temperature measurements for test section 1001 in Utah

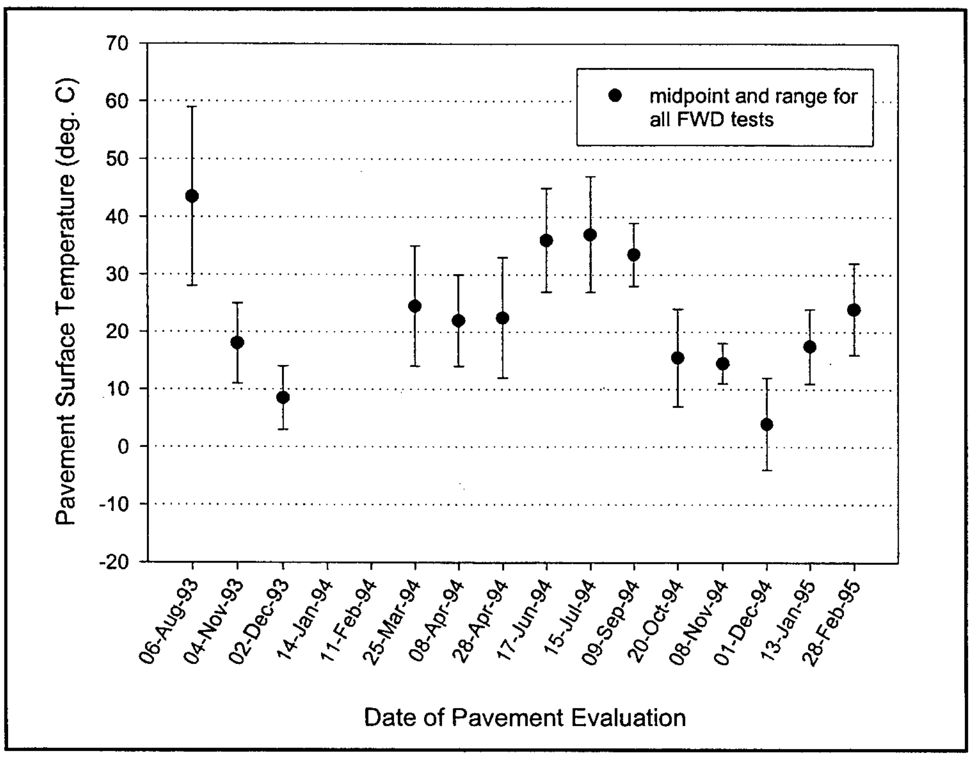


Figure A12. Pavement surface temperature measurements for test section 1001 in Utah

Appendix B
Maximum Error for Measured Deflections

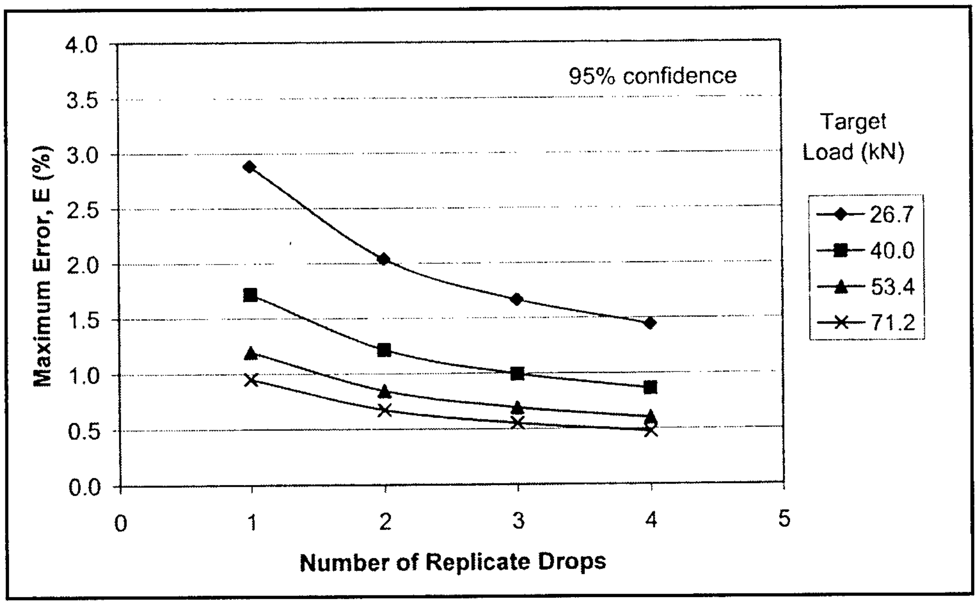


Figure B1. Maximum error for normalized deflection measurements (MA 1002; sensor offset = 0 mm)

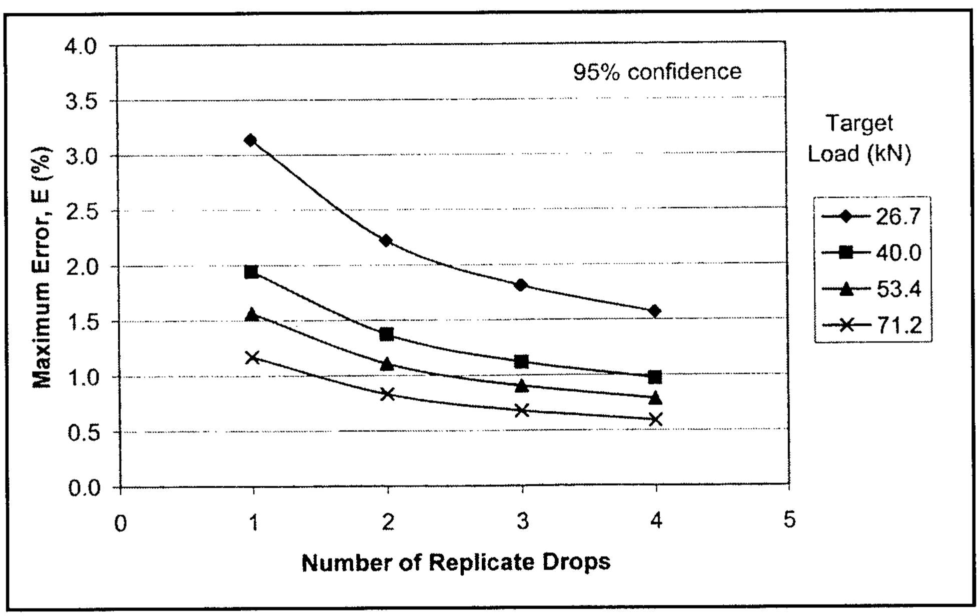


Figure B2. Maximum error for normalized deflection measurements (VT 1002; sensor offset = 0 mm)

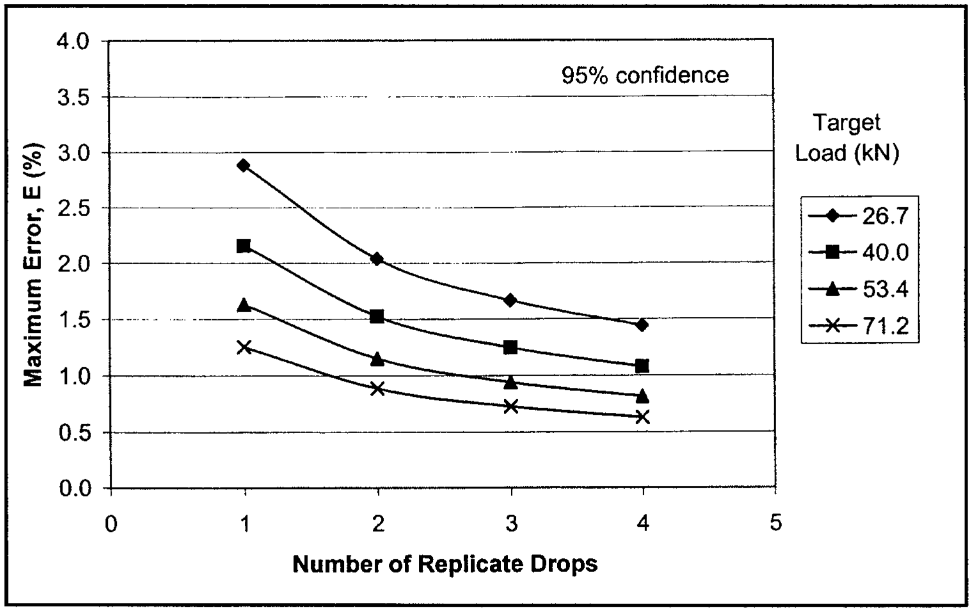


Figure B3. Maximum error for normalized deflection measurements (TX 1060; sensor offset = 0 mm)

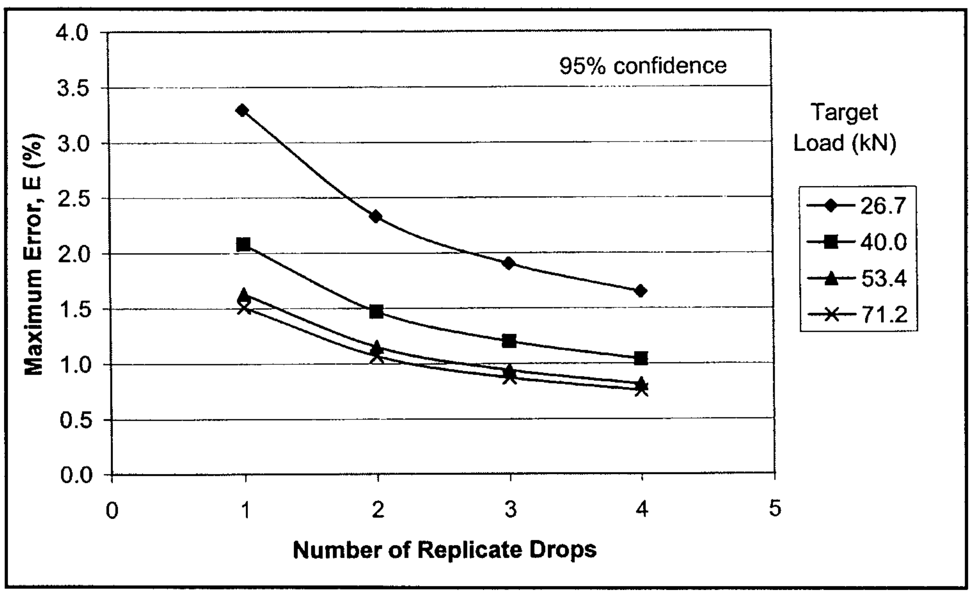


Figure B4. Maximum error for normalized deflection measurements (TX 1122; sensor offset = 0 mm)

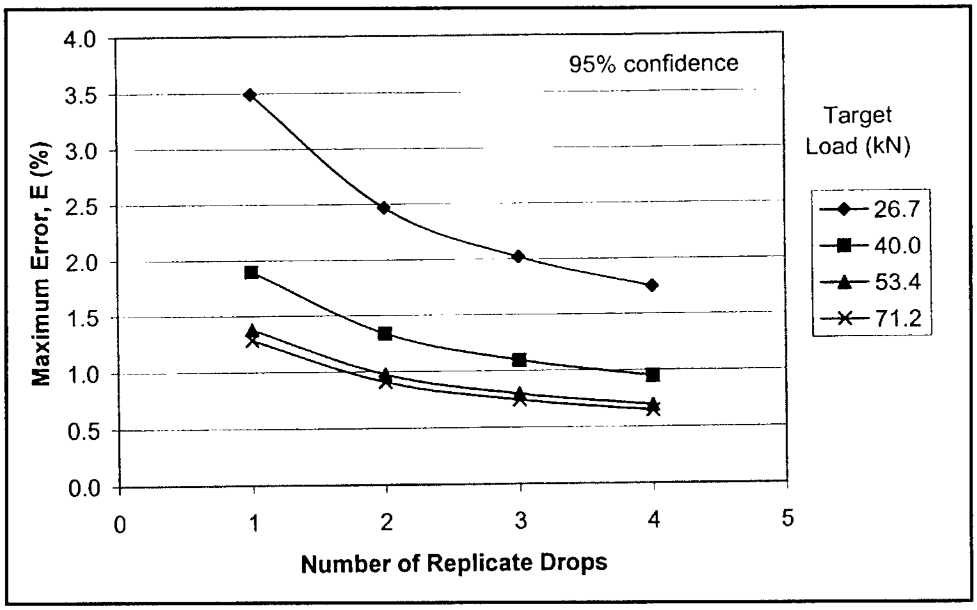


Figure B5. Maximum error for normalized deflection measurements (MT 8129; sensor offset = 0 mm)

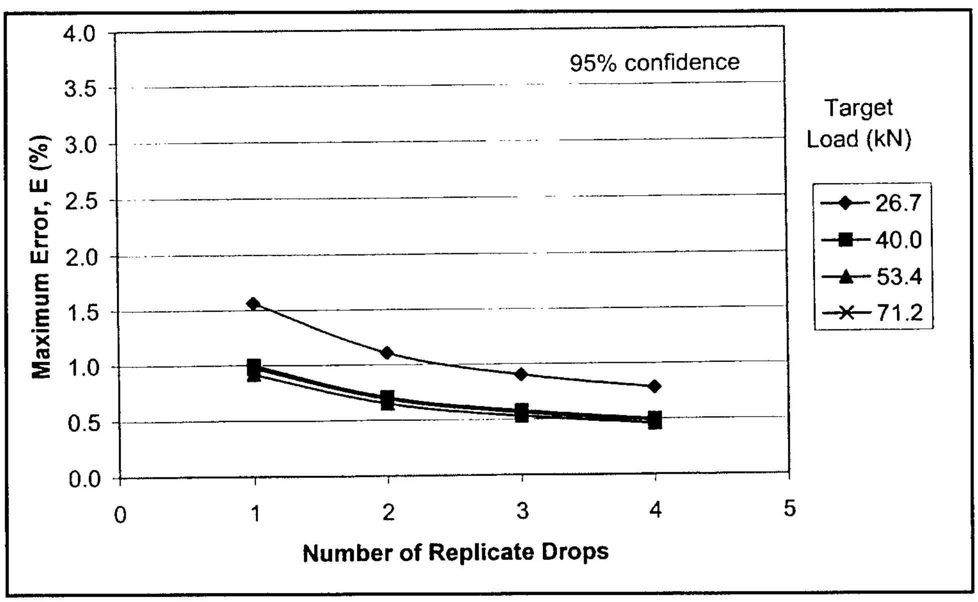


Figure B6. Maximum error for normalized deflection measurements (UT 1001; sensor offset = 0 mm)

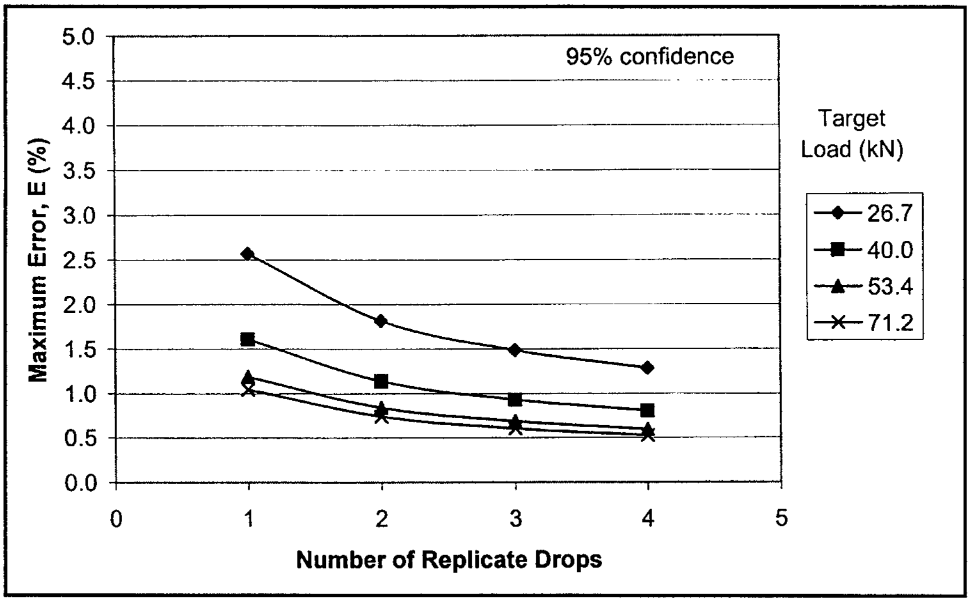


Figure B7. Maximum error for normalized deflection measurements (MA 1002; sensor offset = 203 mm)

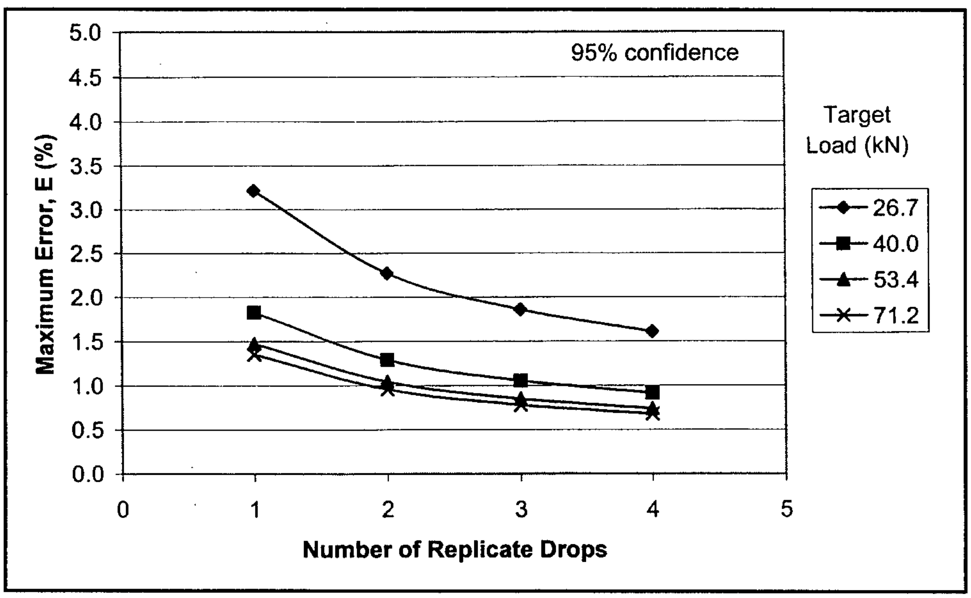


Figure B8. Maximum error for normalized deflection measurements (VT 1002; sensor offset = 203 mm)

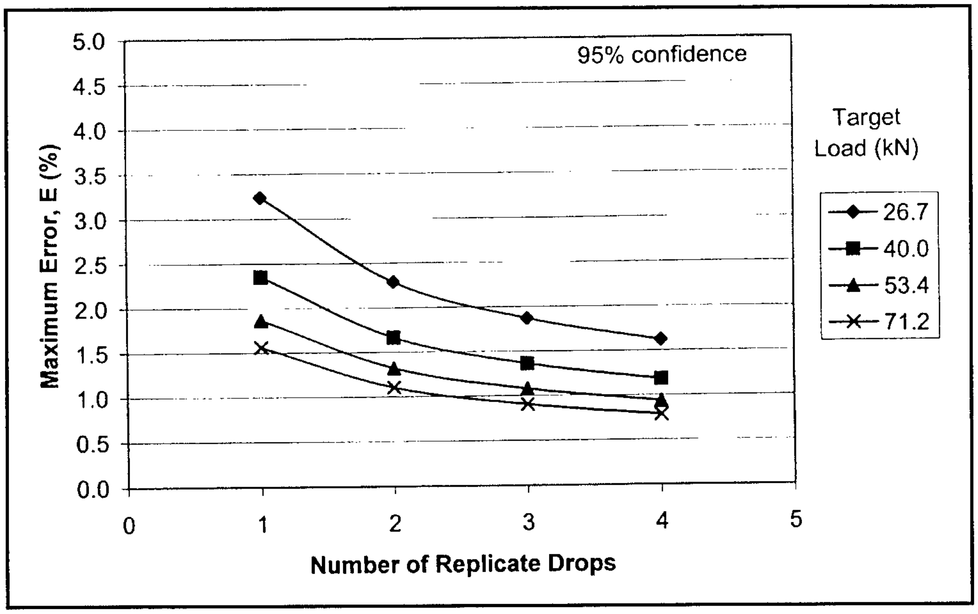


Figure B9. Maximum error for normalized deflection measurements (TX 1060; sensor offset = 203 mm)

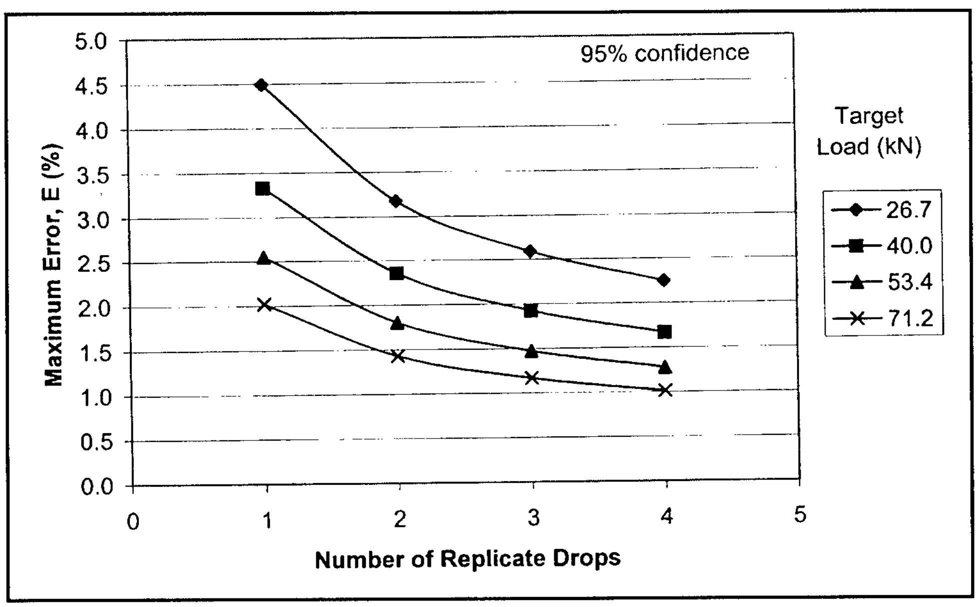


Figure B10. Maximum error for normalized deflection measurements (TX 1122; sensor offset = 203 mm)

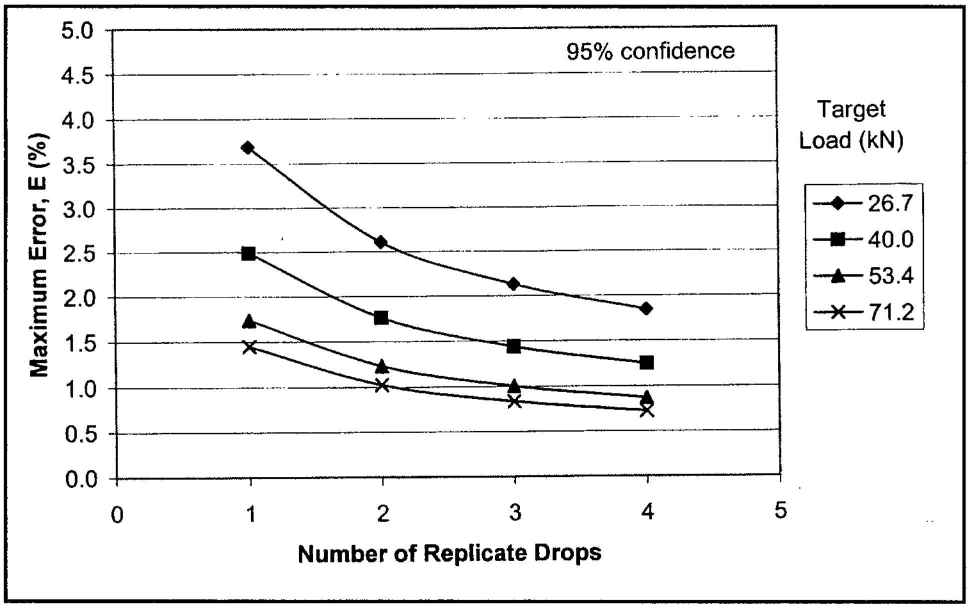


Figure B11. Maximum error for normalized deflection measurements (MT 8129; sensor offset = 203 mm)

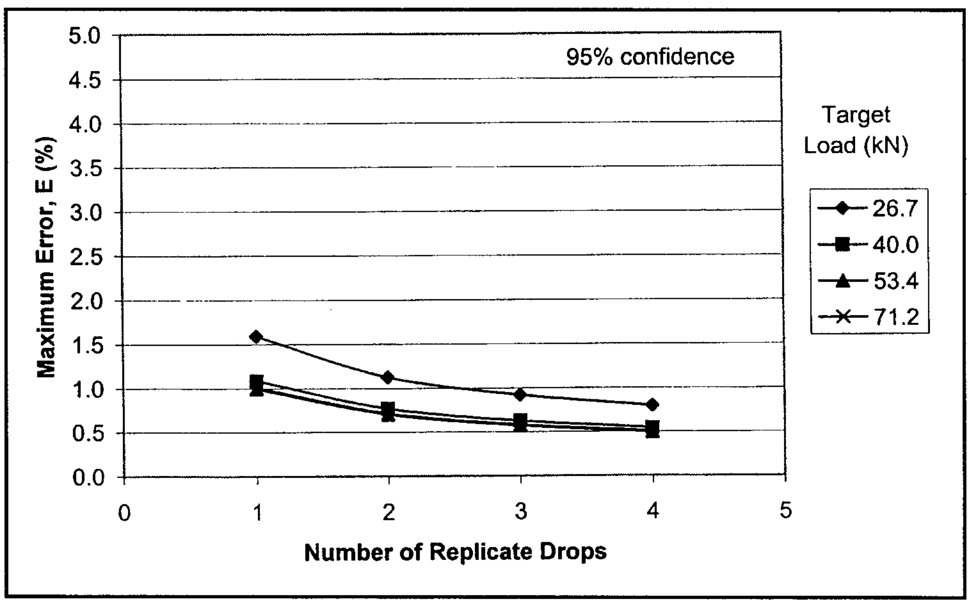


Figure B12. Maximum error for normalized deflection measurements (UT 1001; sensor offset = 203 mm)

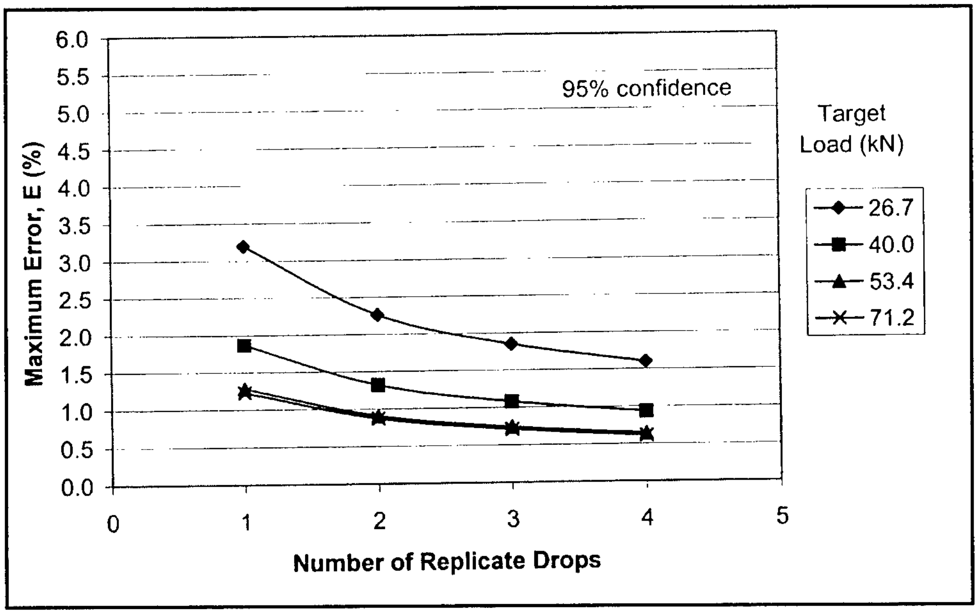


Figure B13. Maximum error for normalized deflection measurements (MA 1002; sensor offset = 305 mm)

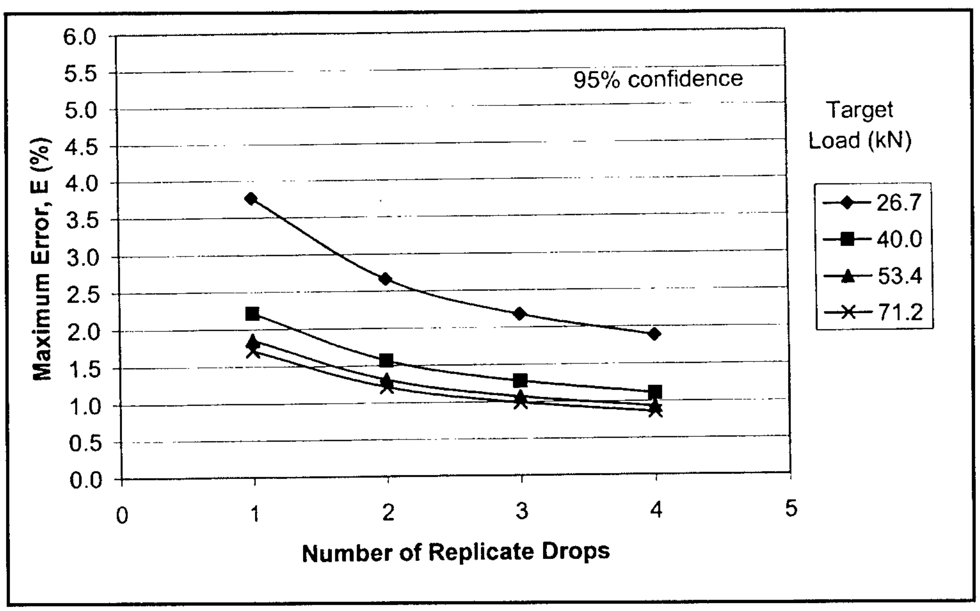


Figure B14. Maximum error for normalized deflection measurements (VT 1002; sensor offset = 305 mm)

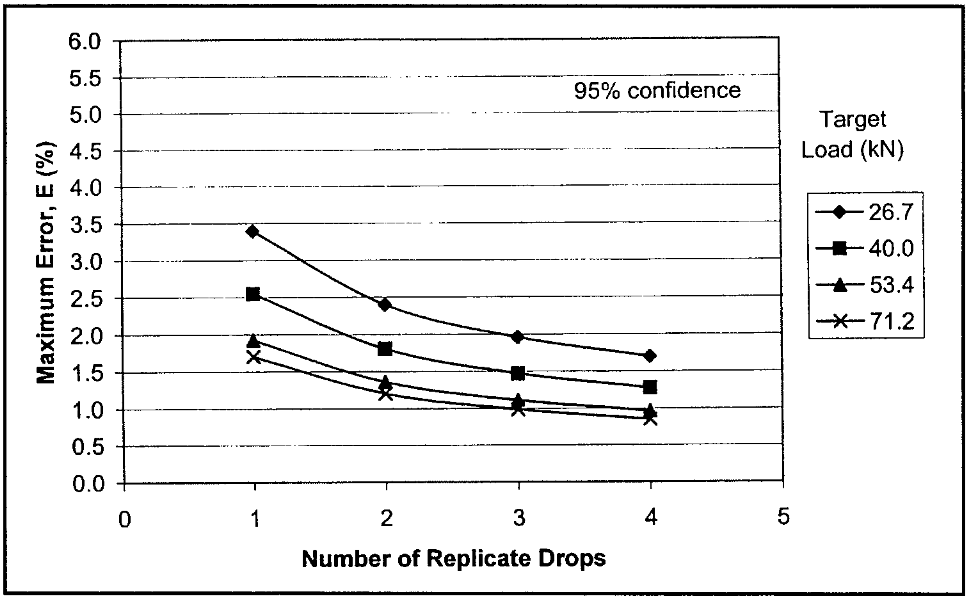


Figure B15. Maximum error for normalized deflection measurements (TX 1060; sensor offset = 305 mm)

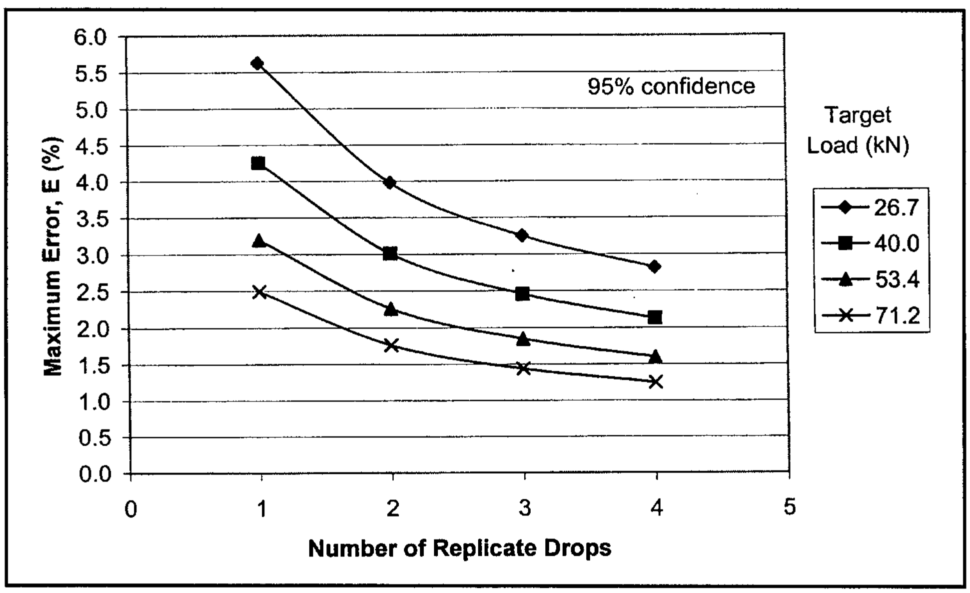


Figure B16. Maximum error for normalized deflection measurements (TX 1122; sensor offset = 305 mm)

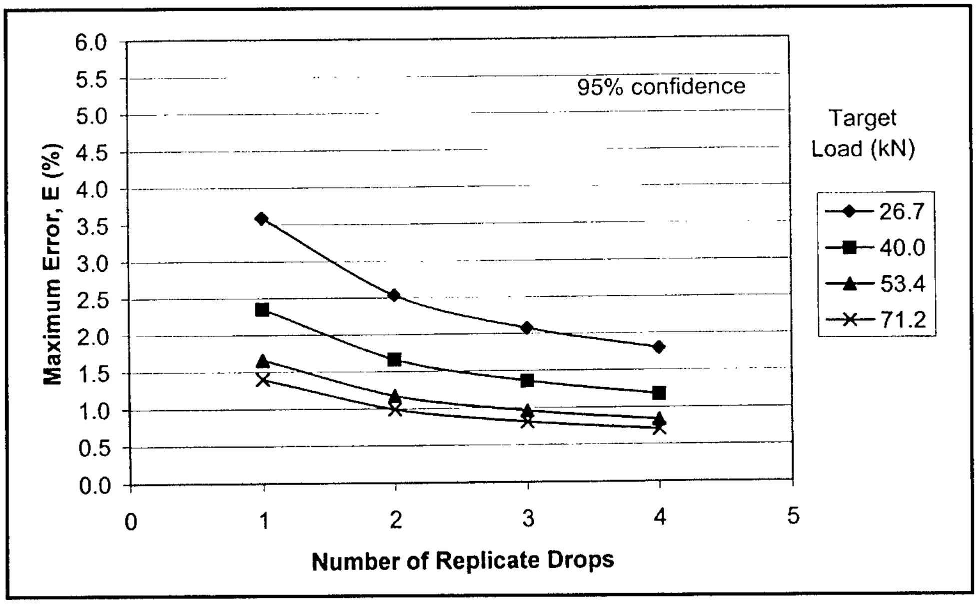


Figure B17. Maximum error for normalized deflection measurements (MT 8129; sensor offset = 305 mm)

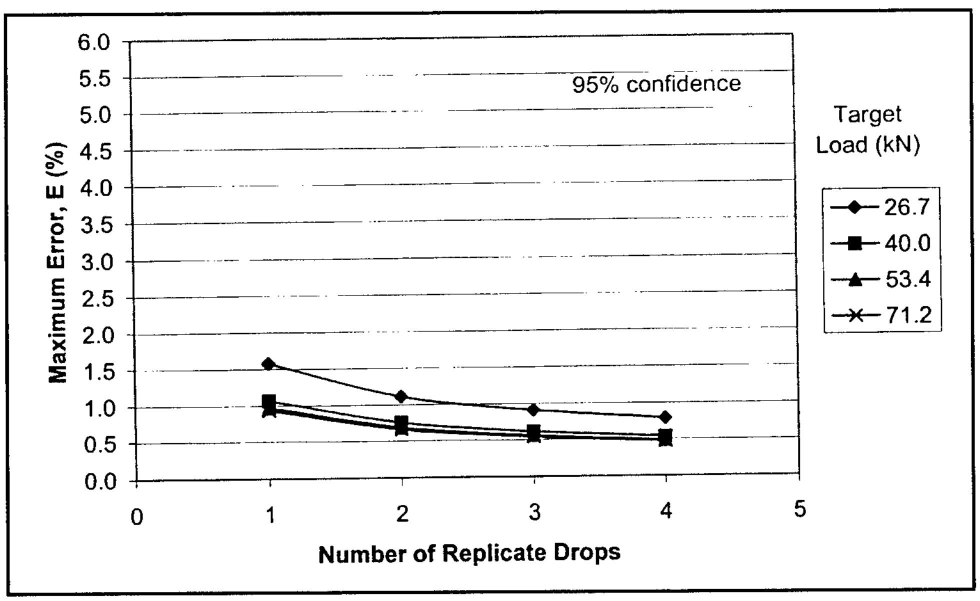


Figure B18. Maximum error for normalized deflection measurements (UT 1001; sensor offset = 305 mm)

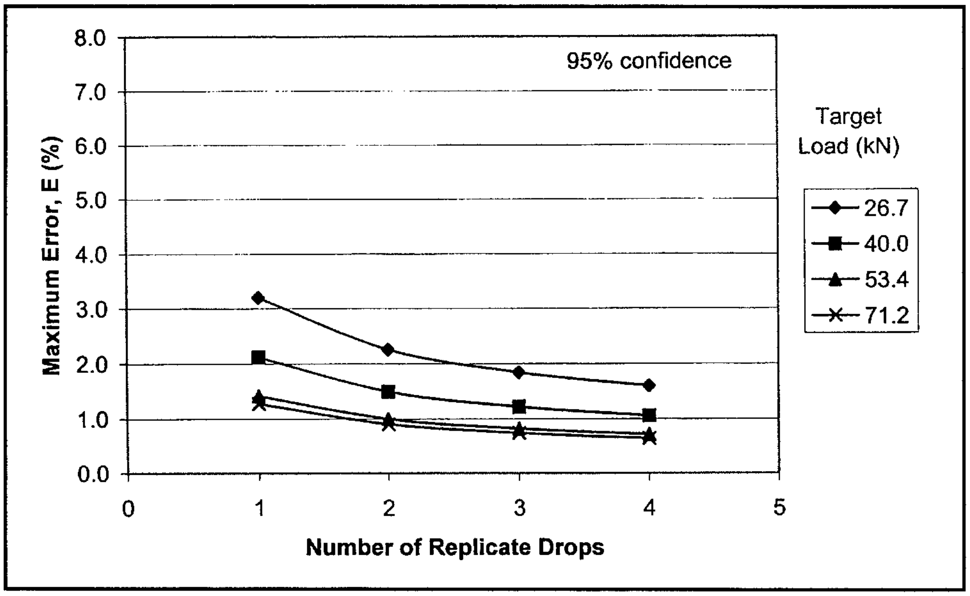


Figure B19. Maximum error for normalized deflection measurements (MA 1002; sensor offset = 457 mm)

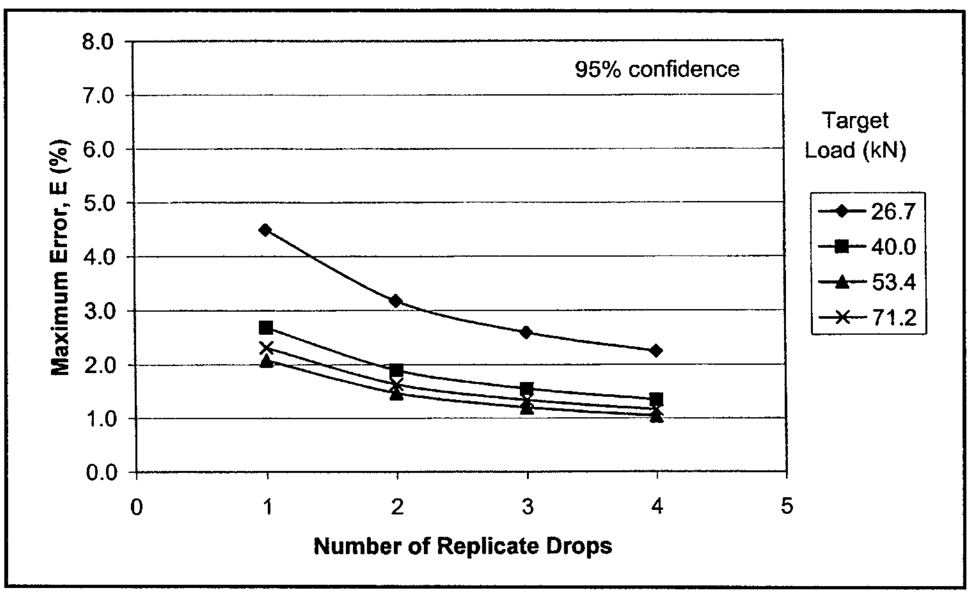


Figure B20. Maximum error for normalized deflection measurements (VT 1002; sensor offset = 457 mm)

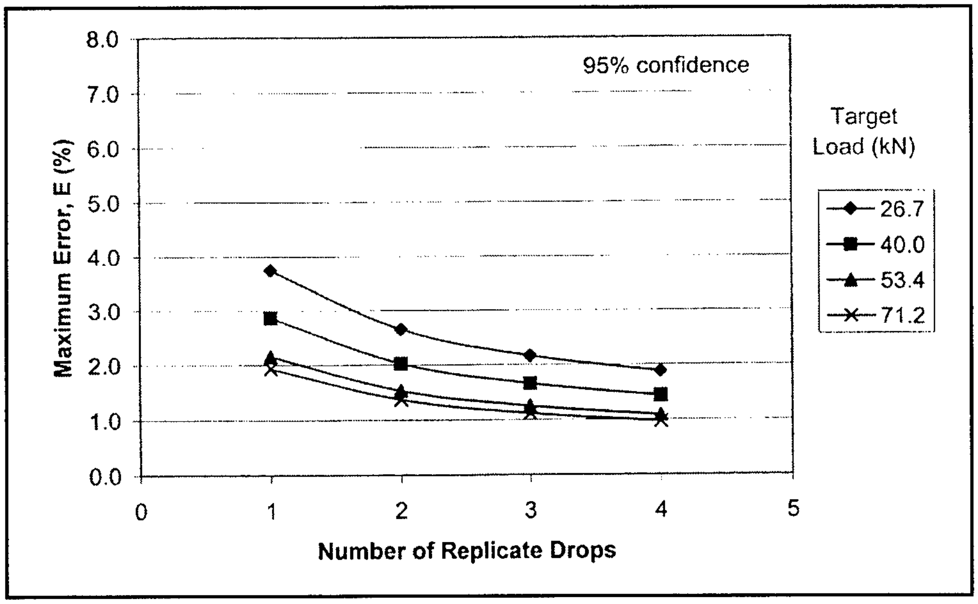


Figure B21. Maximum error for normalized deflection measurements (TX 1060; sensor offset = 457 mm)

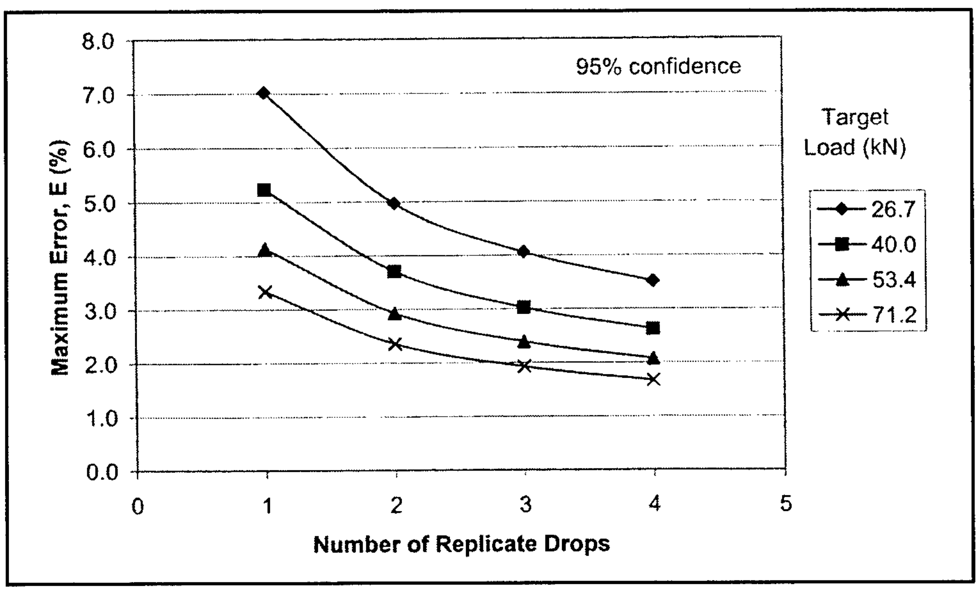


Figure B22. Maximum error for normalized deflection measurements (TX 1122; sensor offset = 457 mm)

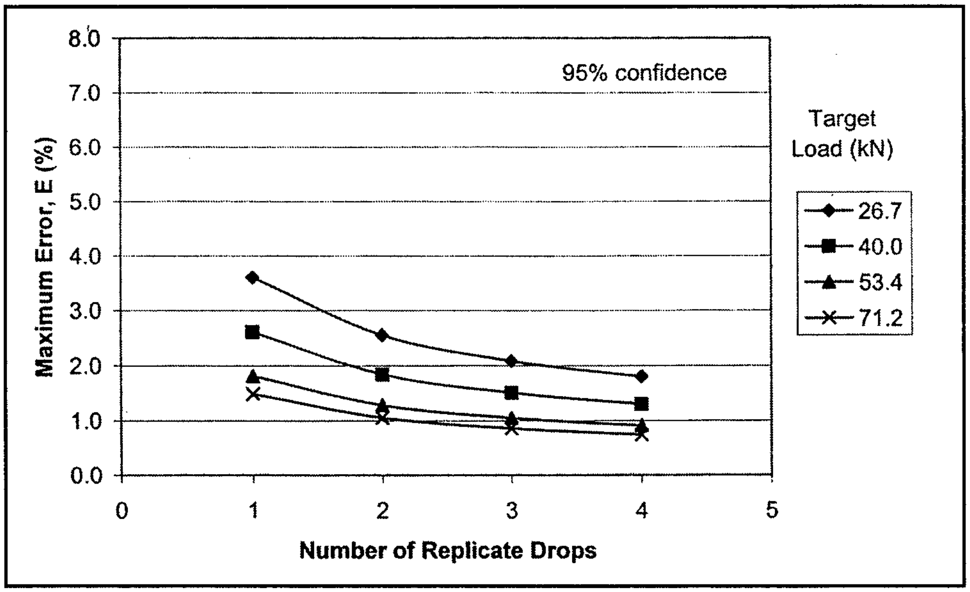


Figure B23. Maximum error for normalized deflection measurements (MT 8129; sensor offset = 457 mm)

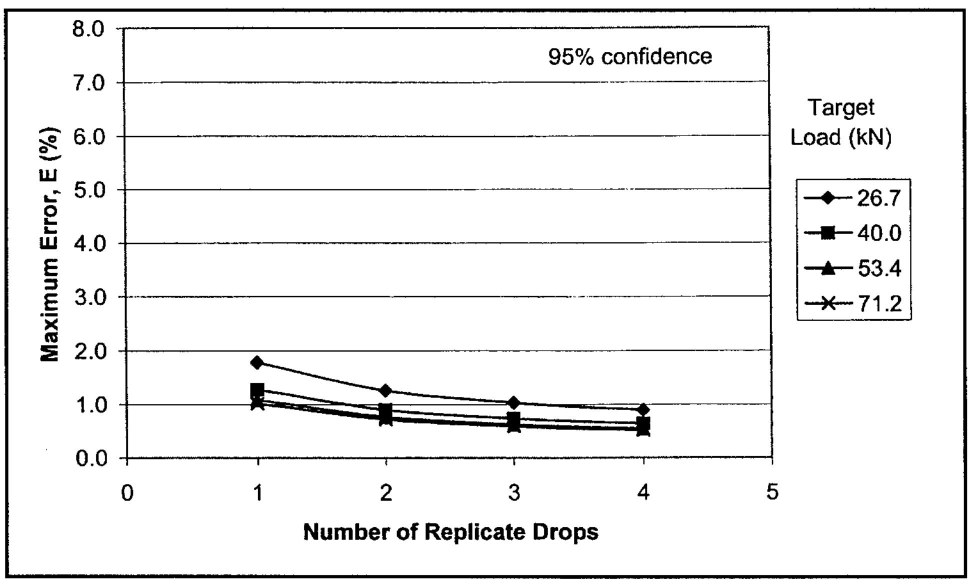


Figure B24. Maximum error for normalized deflection measurements (UT 1001; sensor offset = 457 mm)

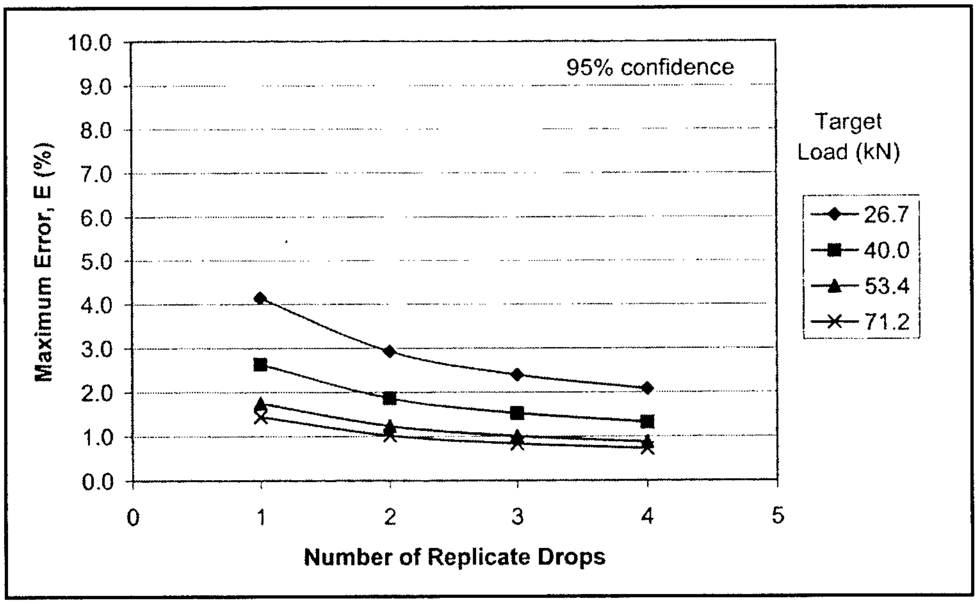


Figure B25. Maximum error for normalized deflection measurements (MA 1002; sensor offset = 610 mm)

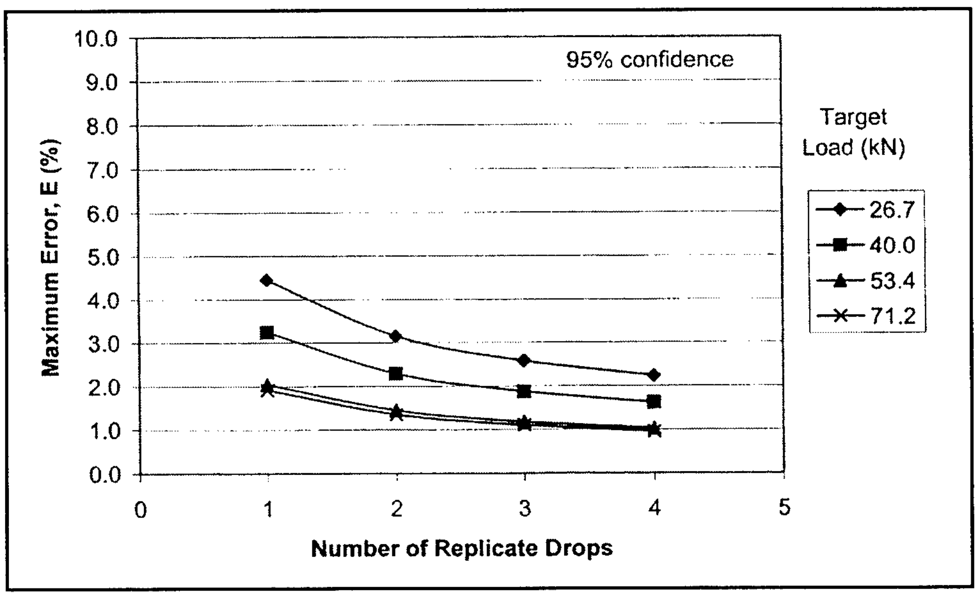


Figure B26. Maximum error for normalized deflection measurements (VT 1002; sensor offset = 610 mm)

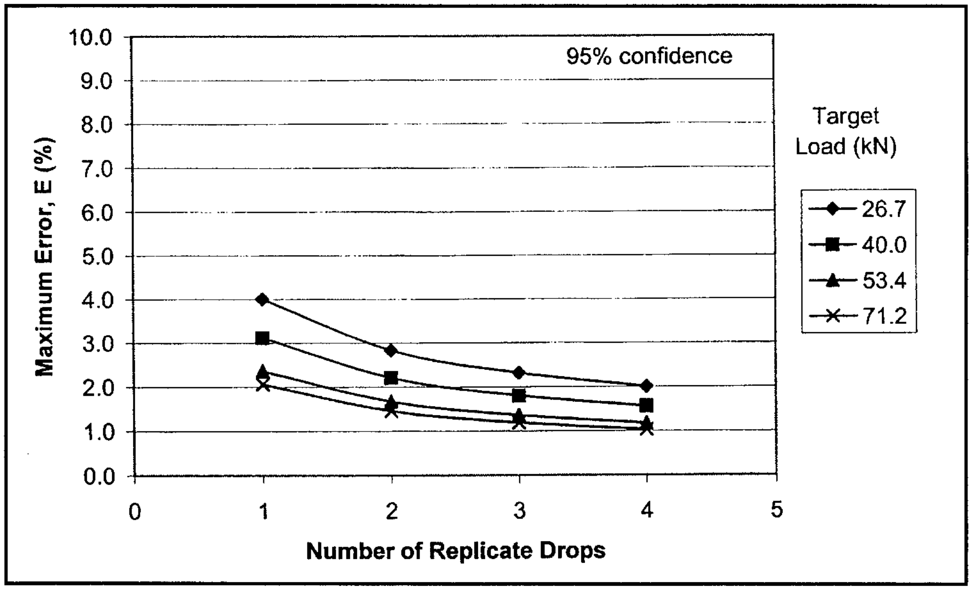


Figure B27. Maximum error for normalized deflection measurements (TX 1060; sensor offset = 610 mm)

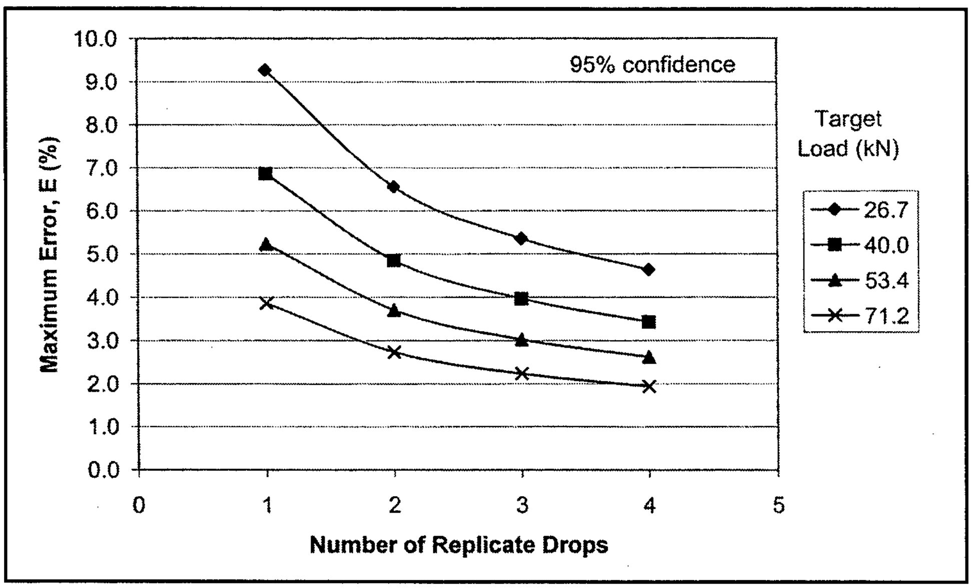


Figure B28. Maximum error for normalized deflection measurements (TX 1122; sensor offset = 610 mm)

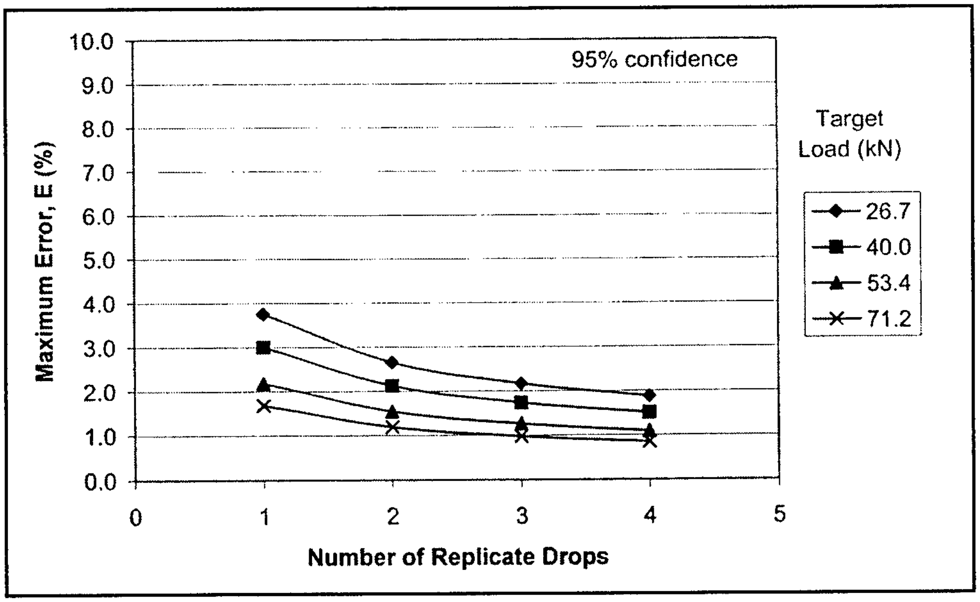


Figure B29. Maximum error for normalized deflection measurements (MT 8129; sensor offset = 610 mm)

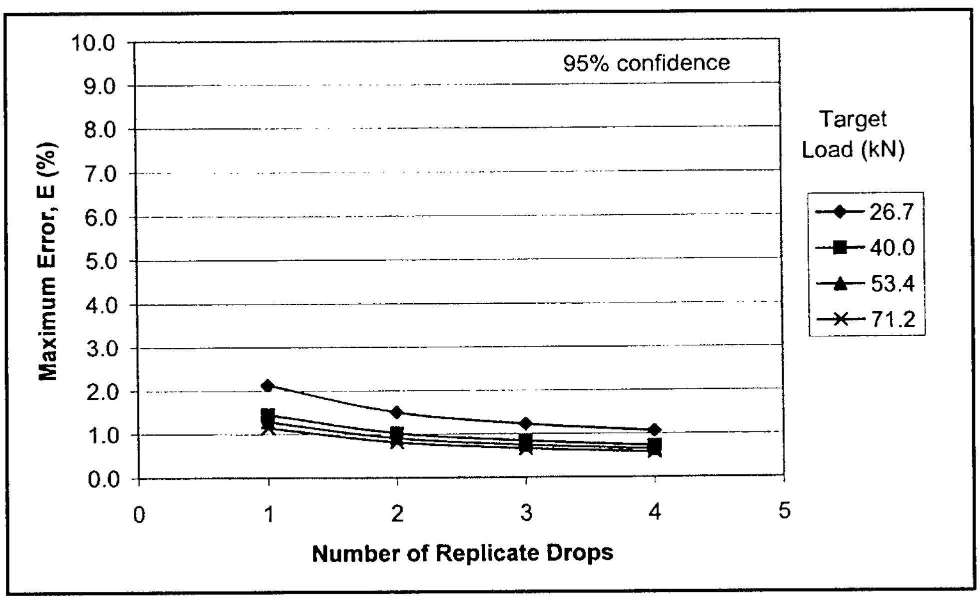


Figure B30. Maximum error for normalized deflection measurements (MT 8129; sensor offset = 610 mm)

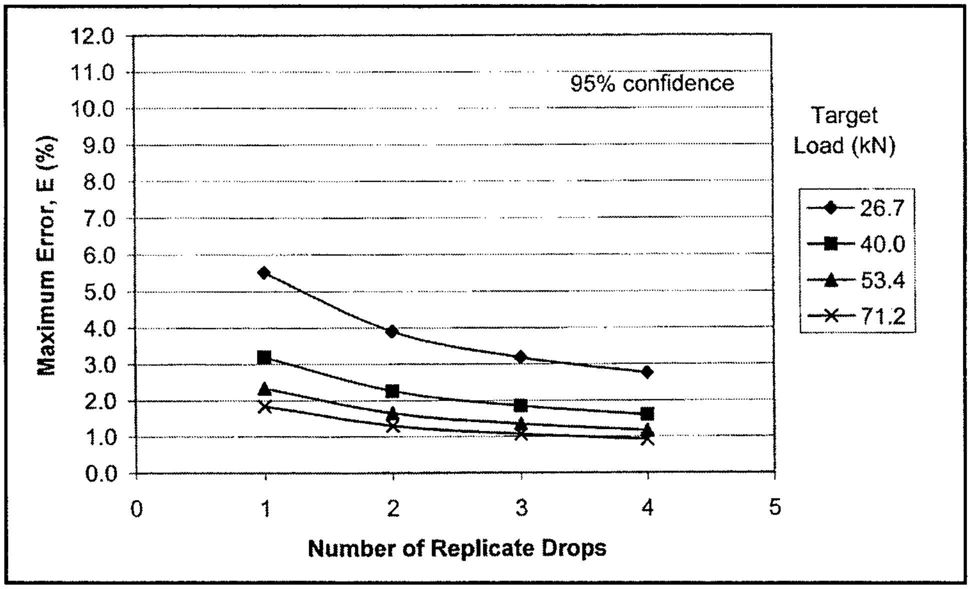


Figure B31. Maximum error for normalized deflection measurements (MA 1002; sensor offset = 914 mm)

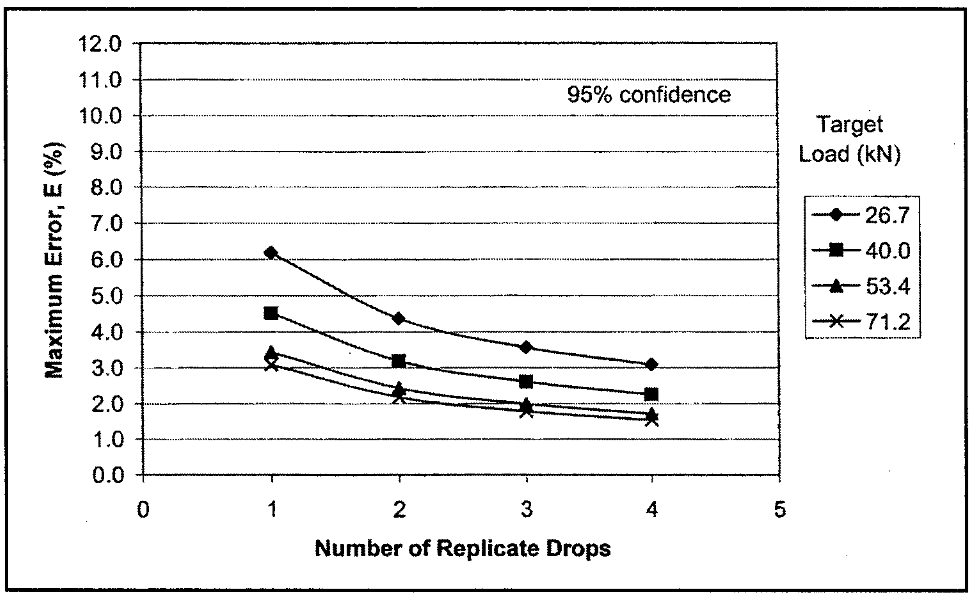


Figure B32. Maximum error for normalized deflection measurements (VT 1002; sensor offset = 914 mm)

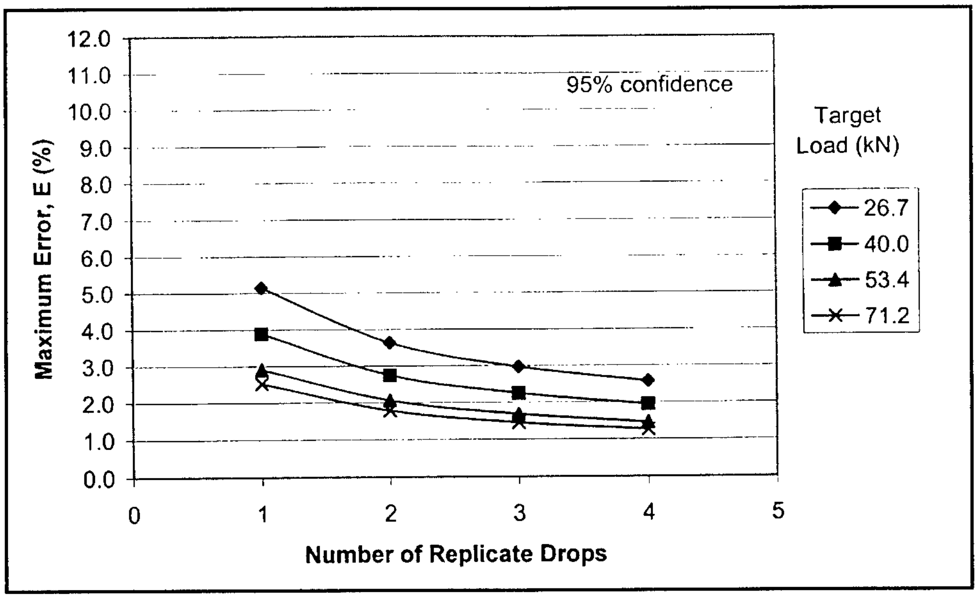


Figure B33. Maximum error for normalized deflection measurements (TX 1060; sensor offset = 914 mm)

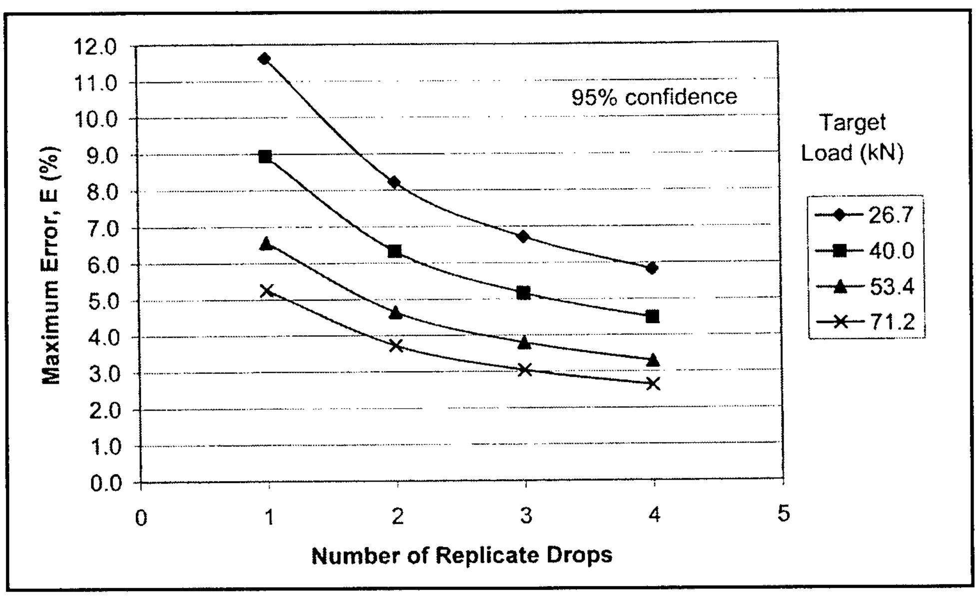


Figure B34. Maximum error for normalized deflection measurements (TX 1122; sensor offset = 914 mm)

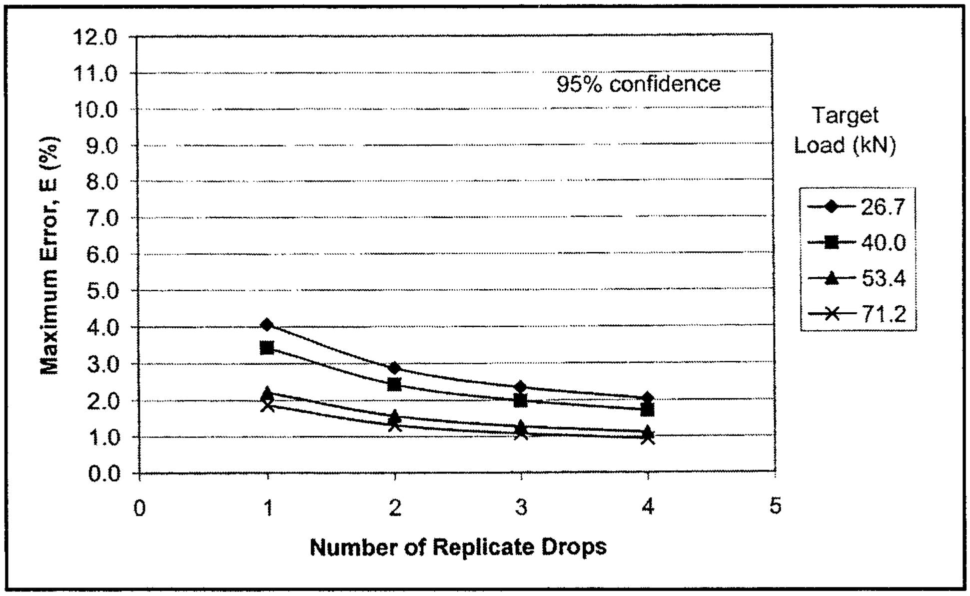


Figure B35. Maximum error for normalized deflection measurements (MT 8129; sensor offset = 914 mm)

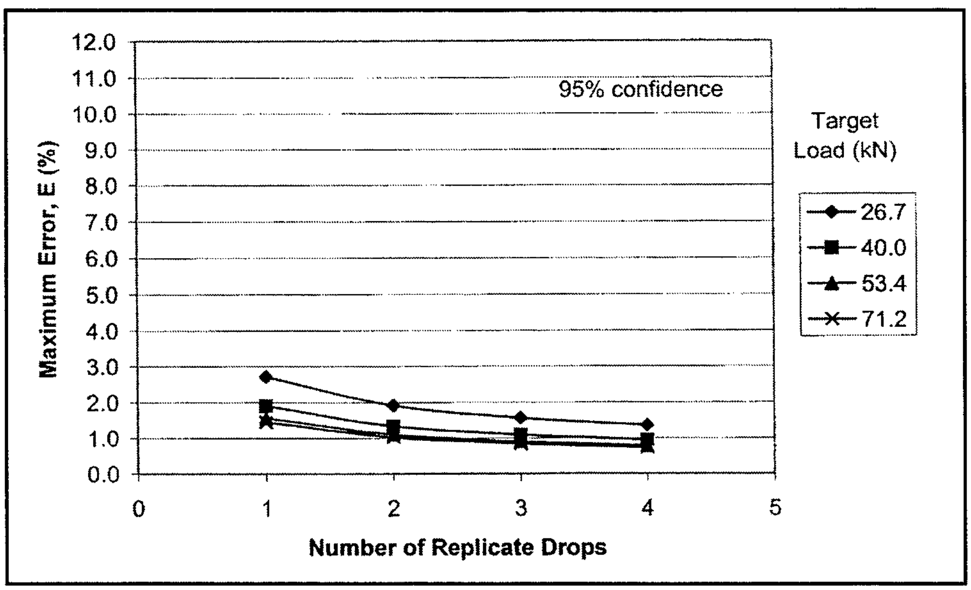


Figure B36. Maximum error for normalized deflection measurements (UT 1001; sensor offset = 914 mm)

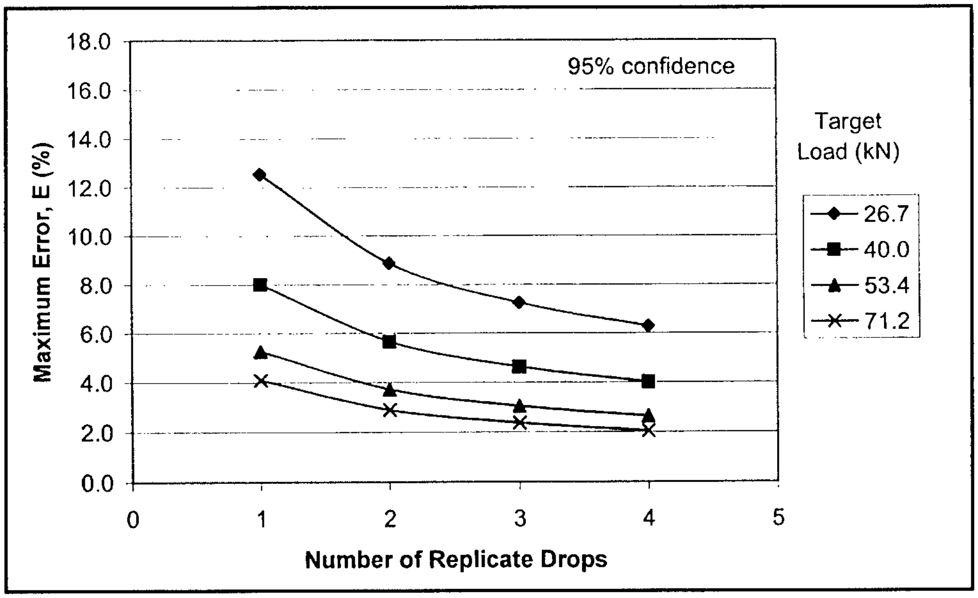


Figure B37. Maximum error for normalized deflection measurements (MA 1002; sensor offset = 1524 mm)

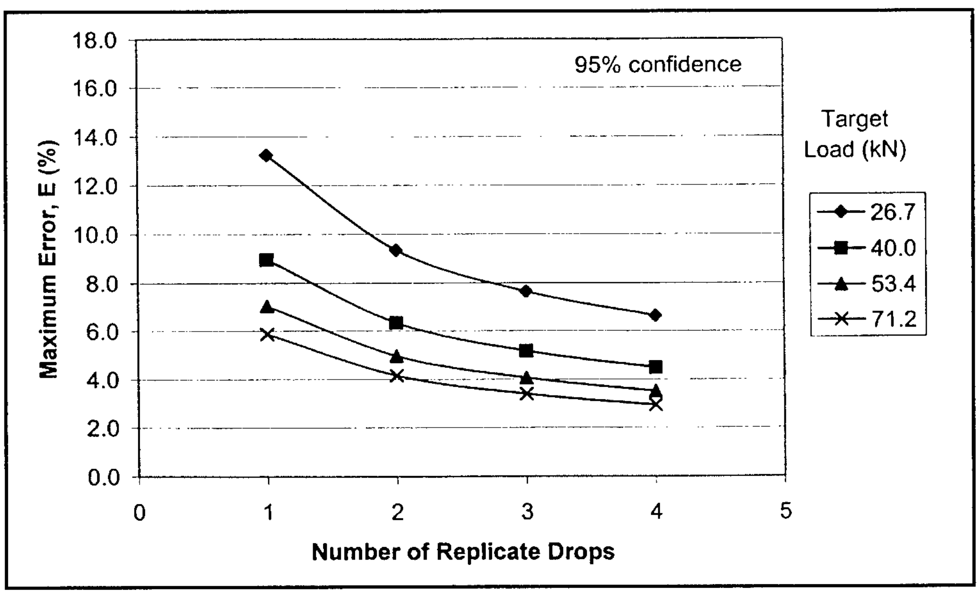


Figure B38. Maximum error for normalized deflection measurements (VT 1002; sensor offset = 1524 mm)

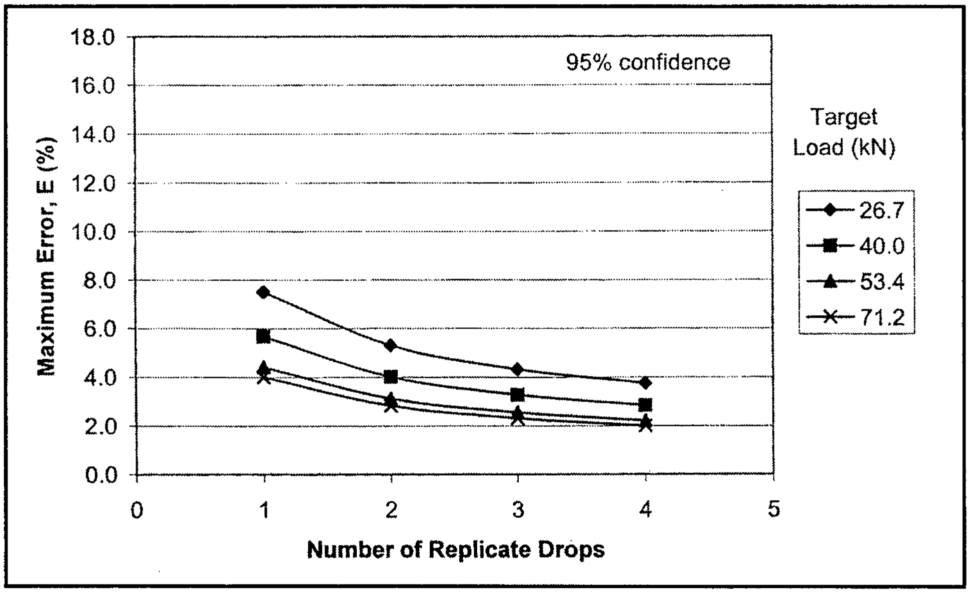


Figure B39. Maximum error for normalized deflection measurements (TX 1060; sensor offset = 1524 mm)

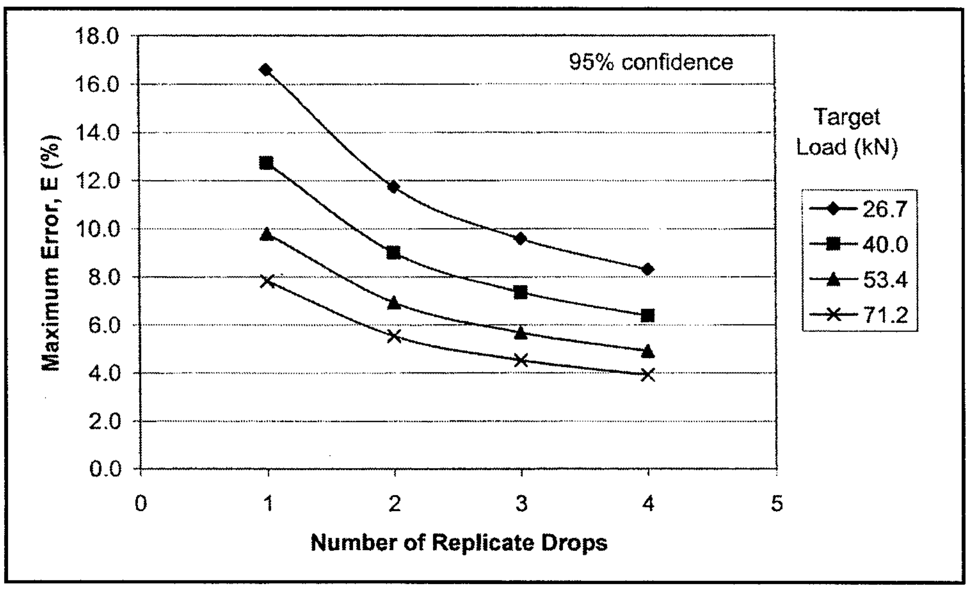


Figure B40. Maximum error for normalized deflection measurements (TX 1122; sensor offset = 1524 mm)

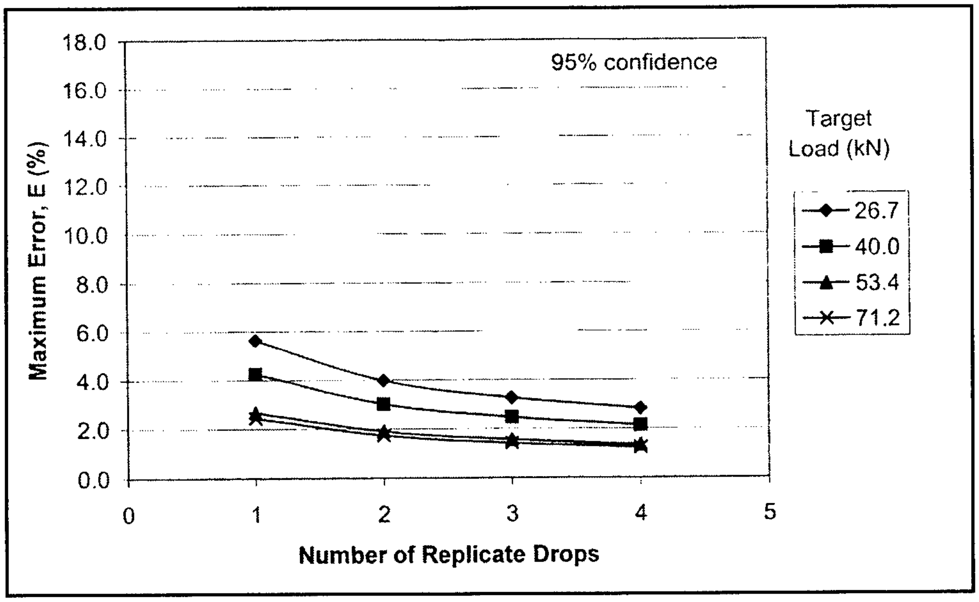


Figure B41. Maximum error for normalized deflection measurements (MT 8129; sensor offset = 1524 mm)

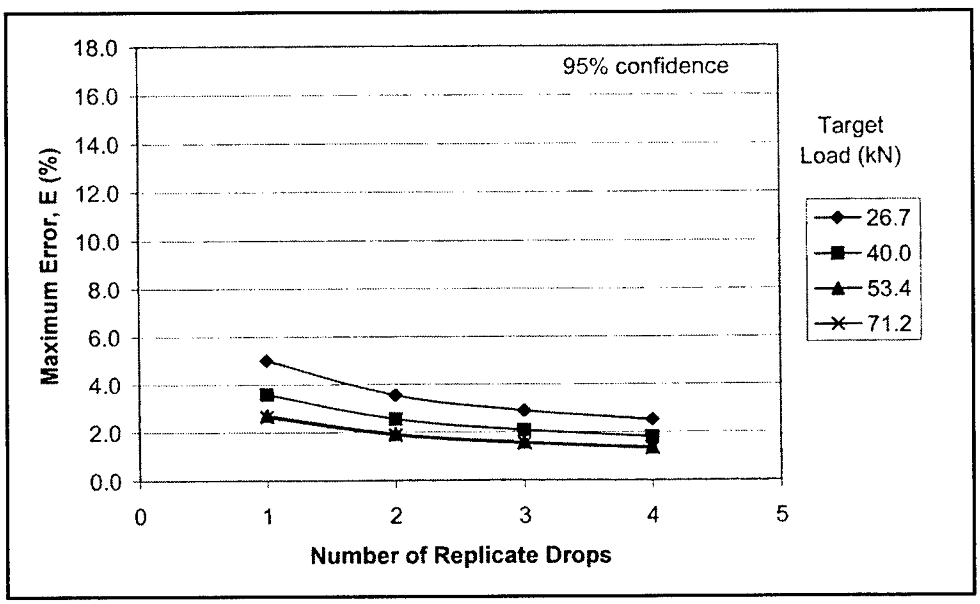


Figure B42. Maximum error for normalized deflection measurements (UT 1001; sensor offset = 1524 mm)

Appendix C
Impulse Stiffness Moduli

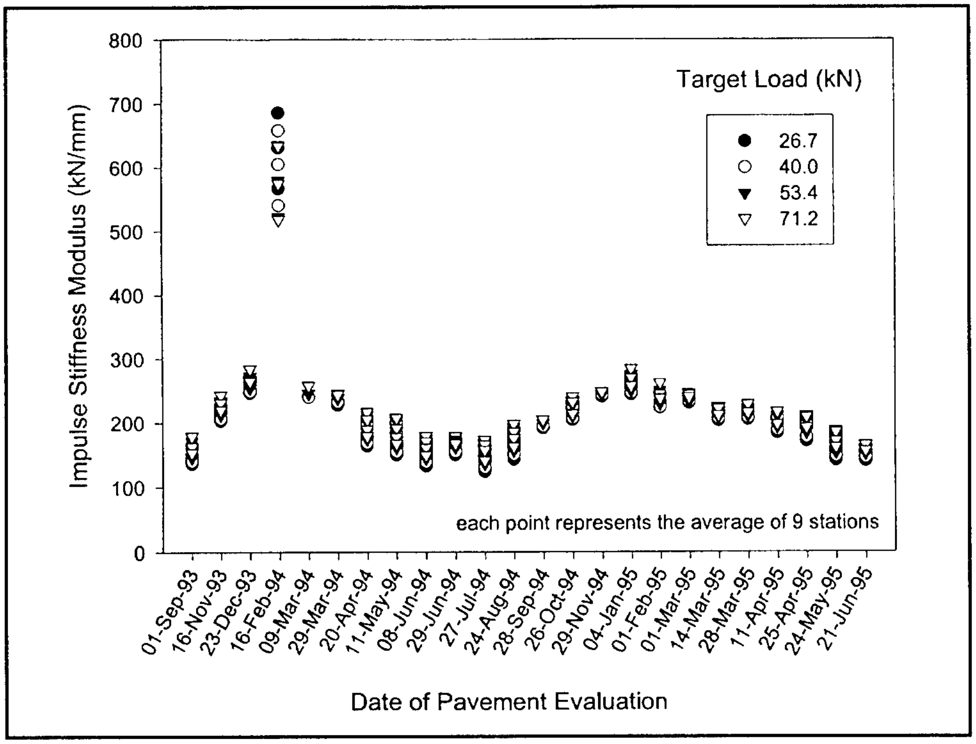


Figure C1. Impulse stiffness moduli for the midlane test path of test section 1002 in Massachusetts

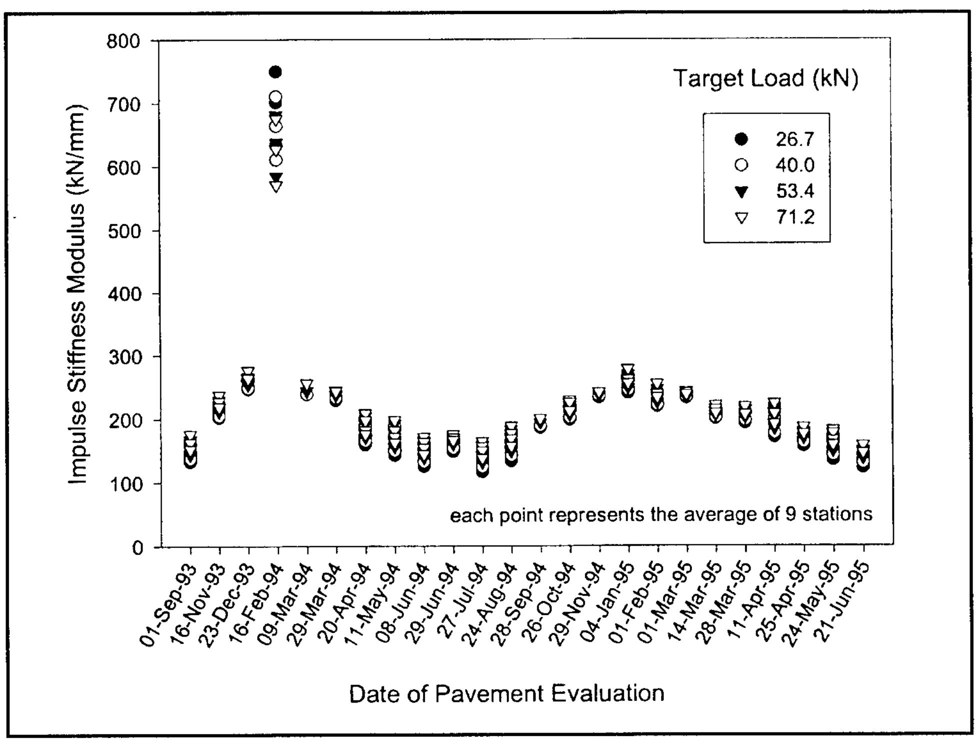


Figure C2. Impulse stiffness moduli for the outside wheelpath of test section 1002 in Massachusetts

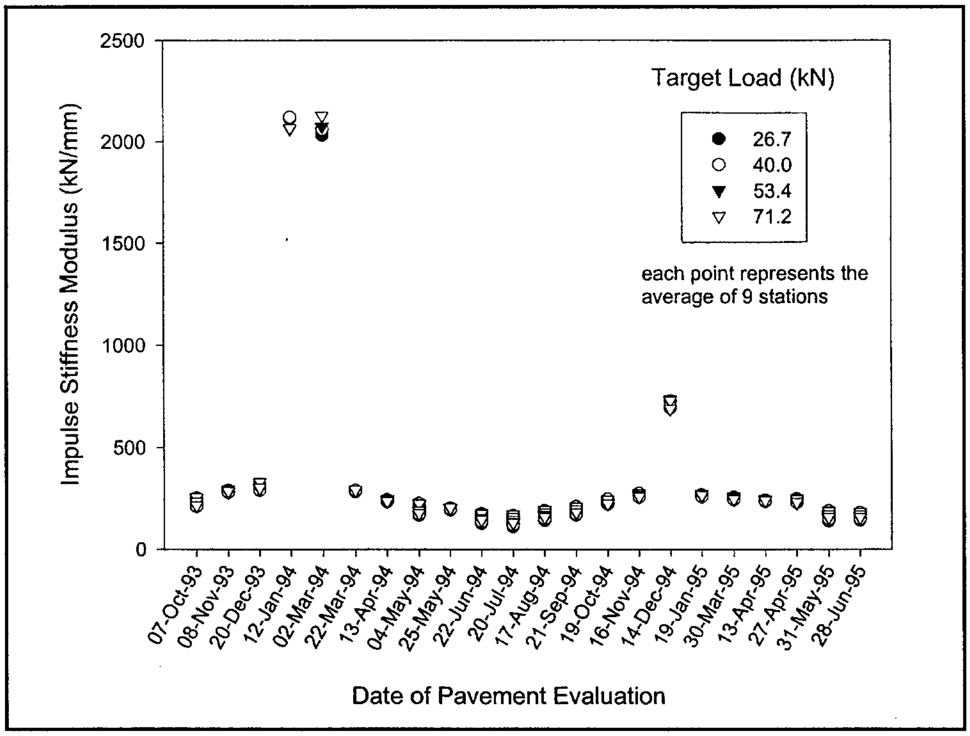


Figure C3. Impulse stiffness moduli for the midlane test path of test section 1002 in Vermont

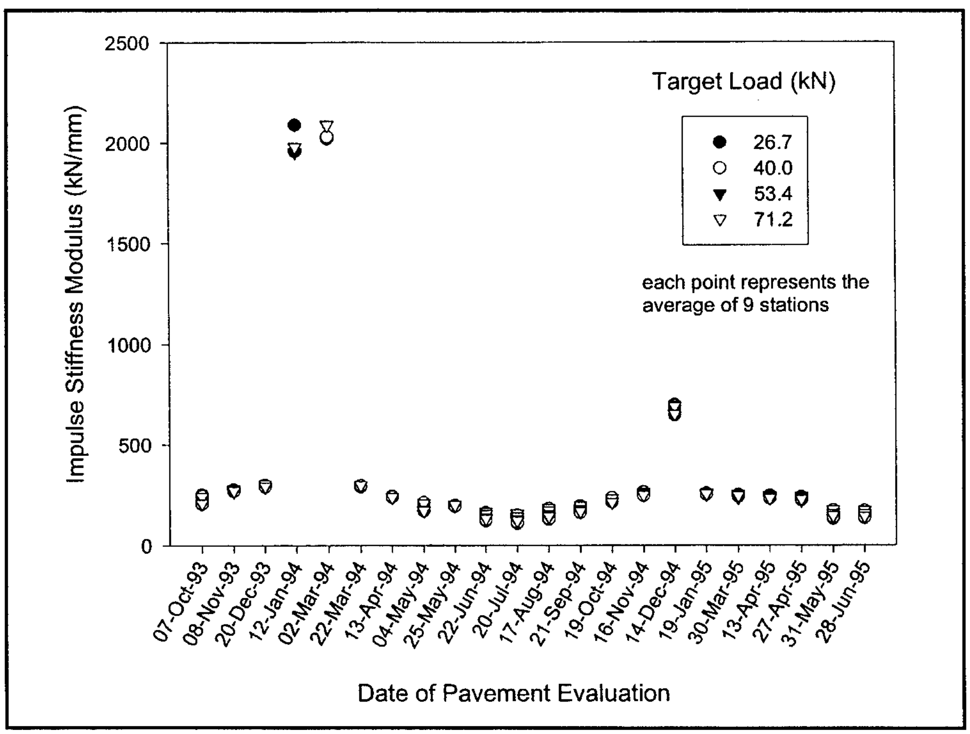


Figure C4. Impulse stiffness moduli for the outside wheelpath of test section 1002 in Vermont

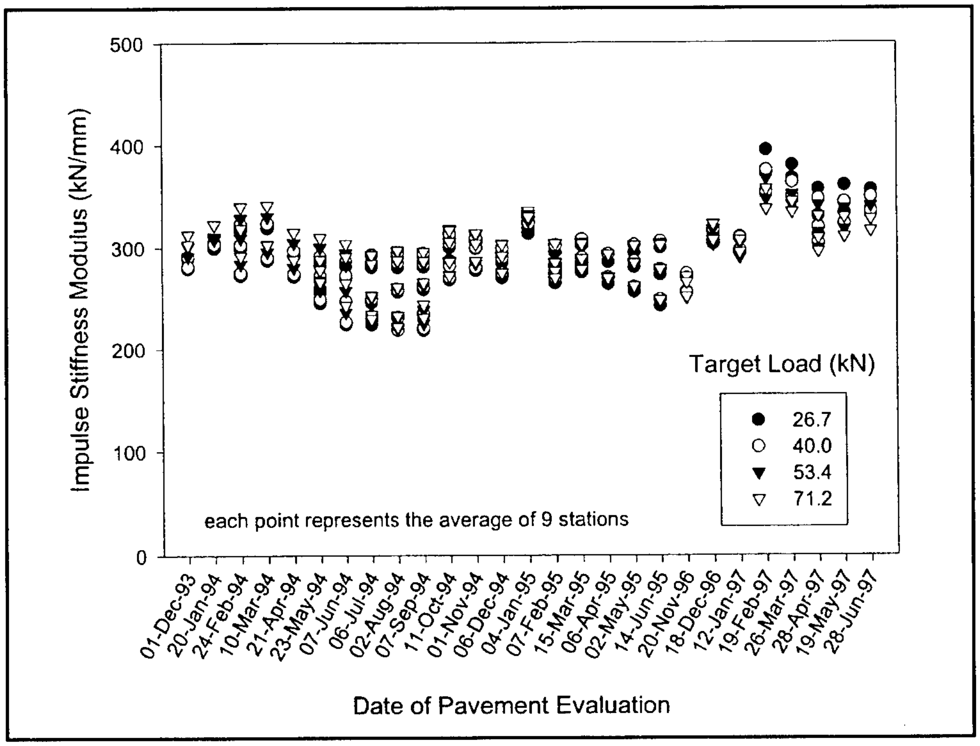


Figure C5. Impulse stiffness moduli for the midlane test path of test section 1060 in Texas

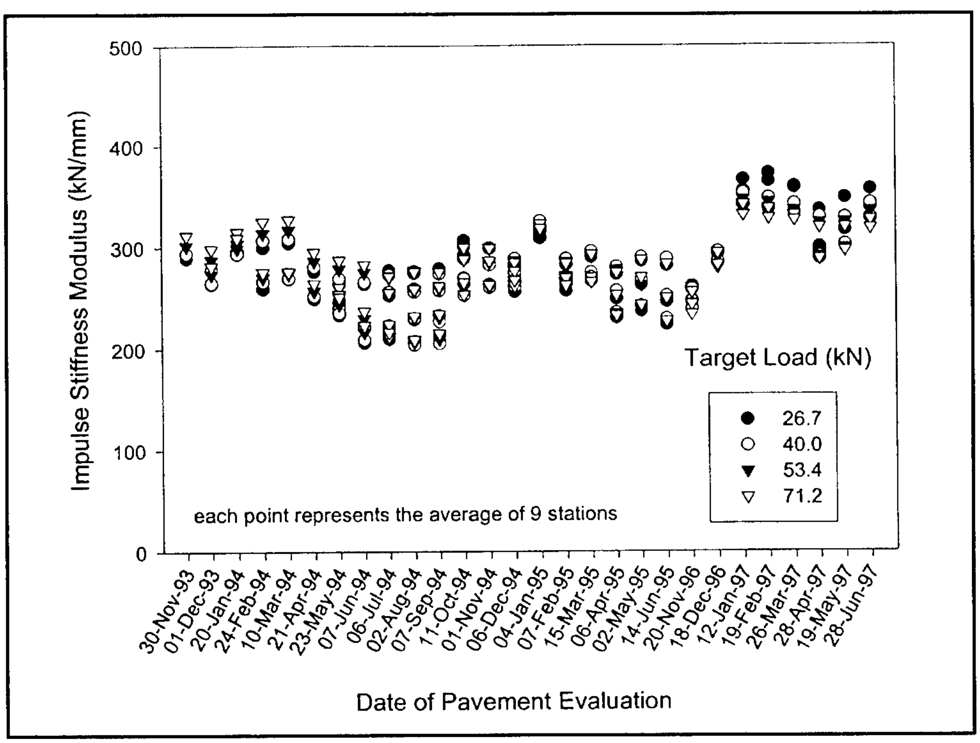


Figure C6. Impulse stiffness moduli for the outside wheelpath of test section 1060 in Texas

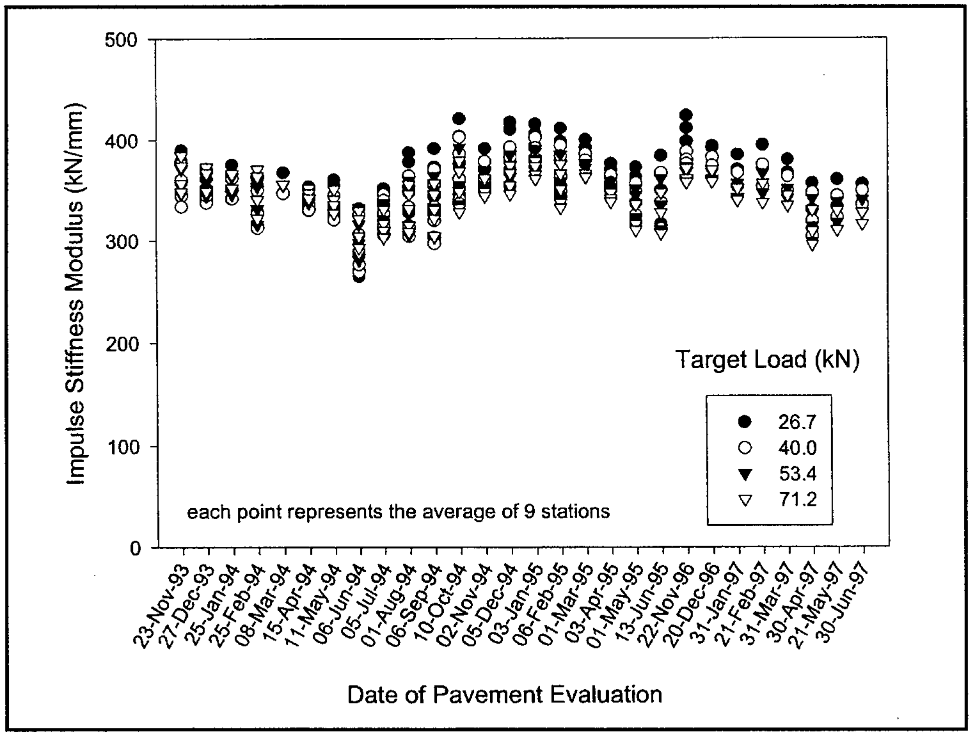


Figure C7. Impulse stiffness moduli for the midlane test path of test section 1122 in Texas

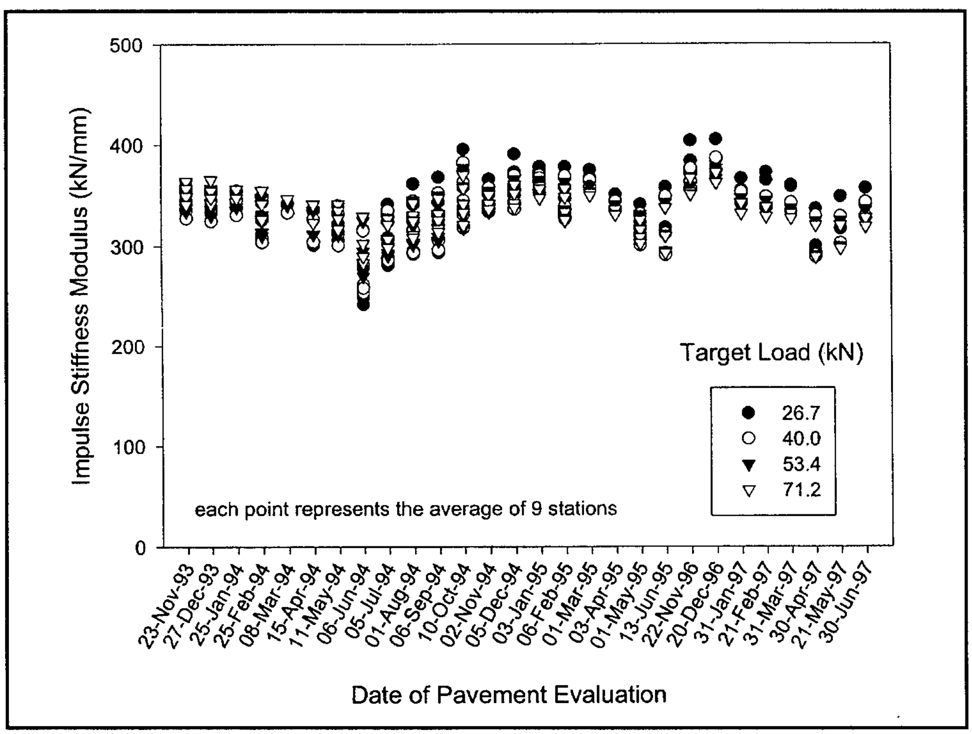


Figure C8. Impulse stiffness moduli for the outside wheelpath of test section 1122 in Texas

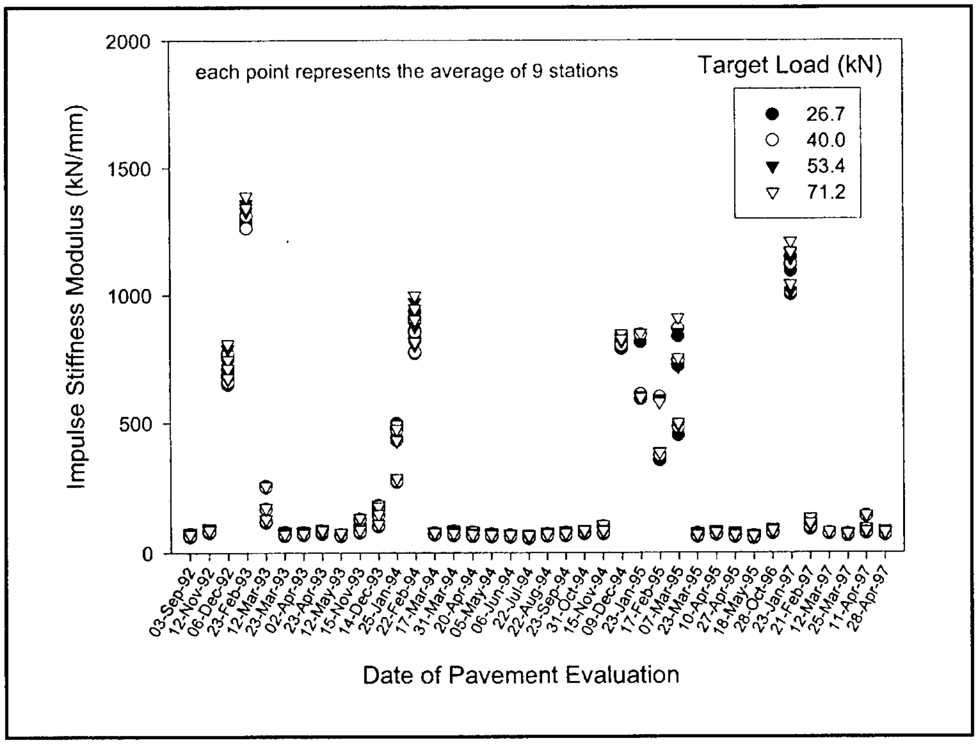


Figure C9. Impulse stiffness moduli for the midlane test path of test section 8129 in Montana

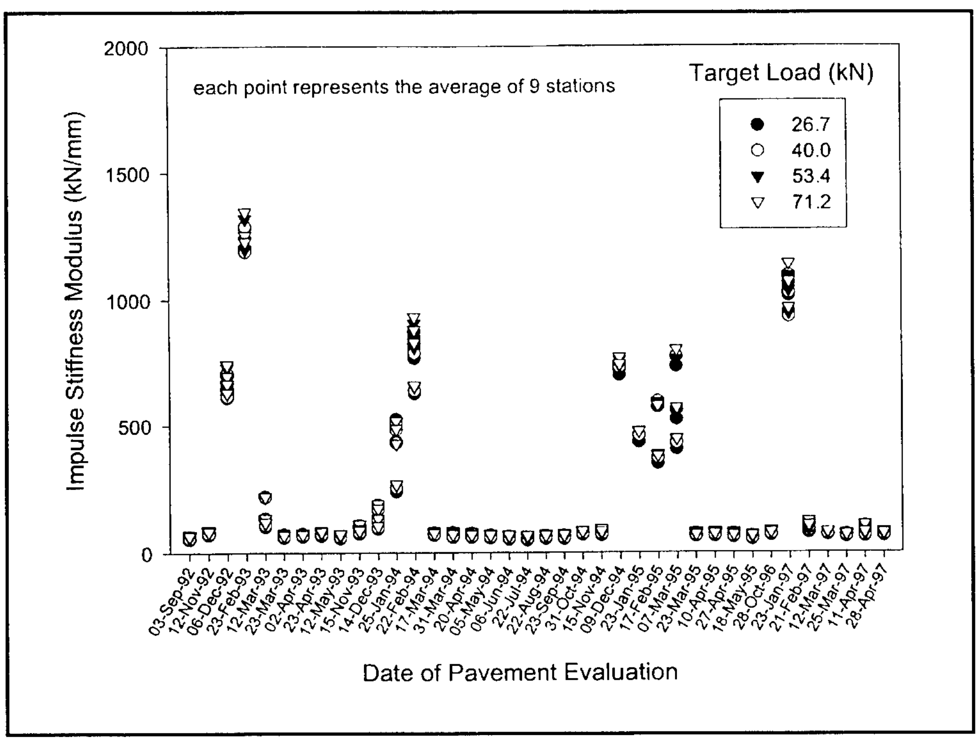


Figure C10. Impulse stiffness moduli for the outside wheelpath of test section 8129 in Montana

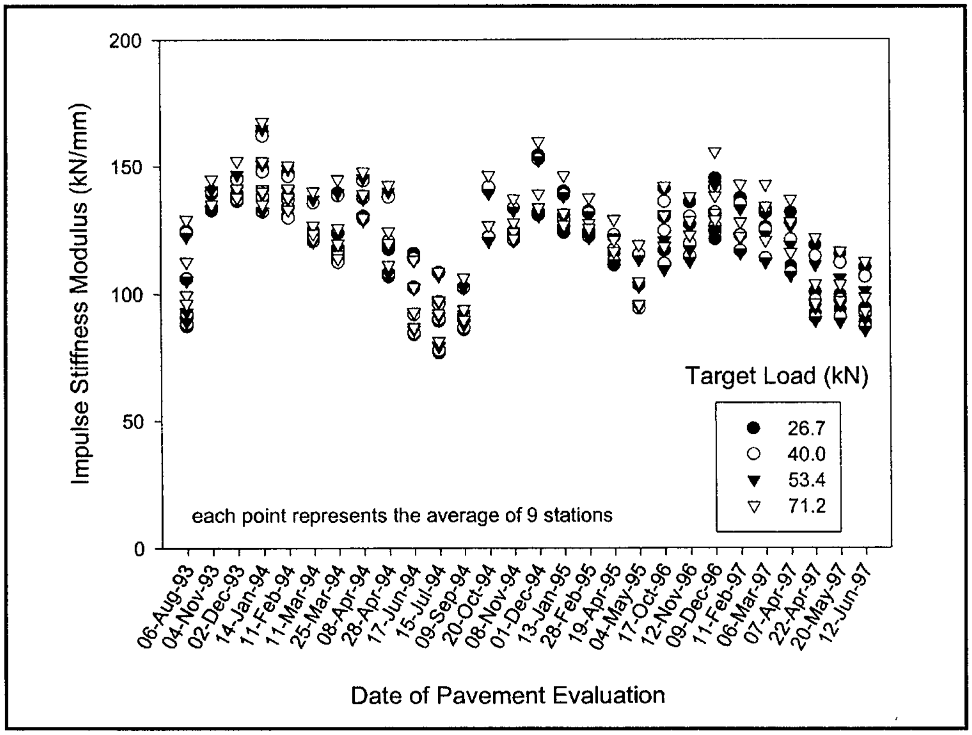


Figure C11. Impulse stiffness moduli for the midlane test path of test section 1001 in Utah

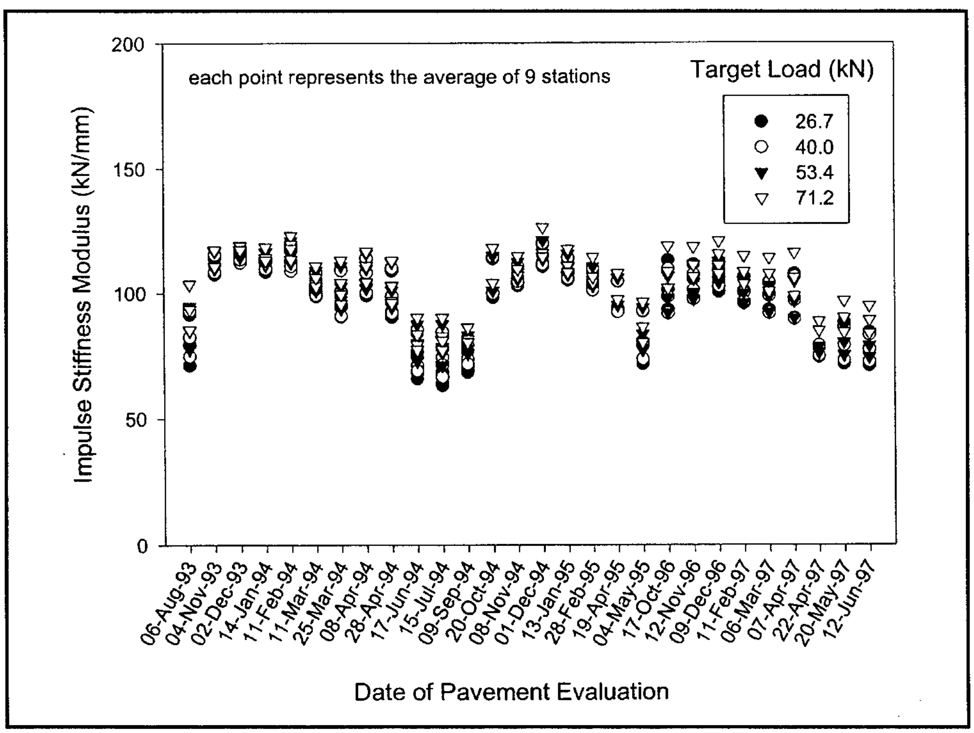


Figure C12. Impulse stiffness moduli for the outside wheelpath of test section 1001 in Utah

Appendix D
Variability Among Falling-Weight Deflectometer Test Stations

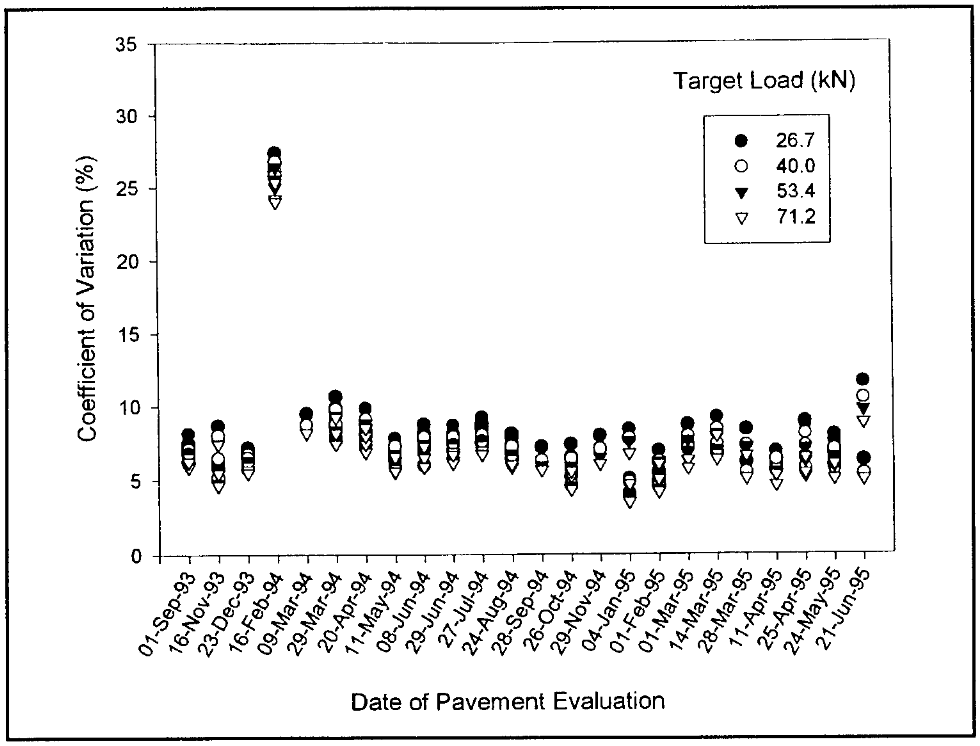


Figure D1. Variability among stations for the midlane test path of test section 1002 in Massachusetts

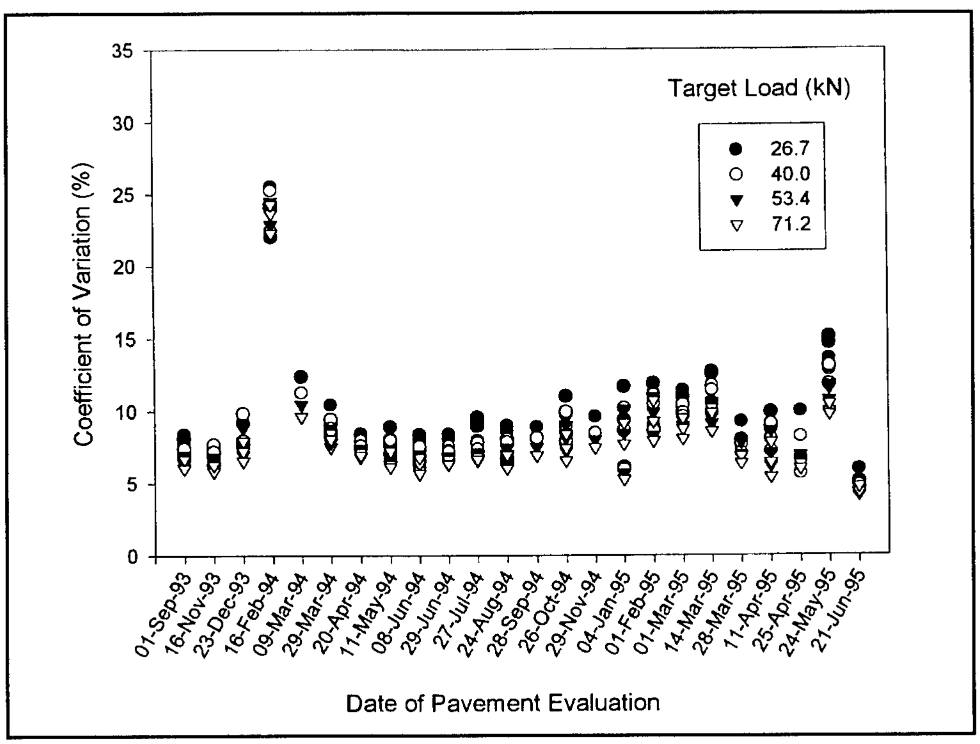


Figure D2. Variability among stations for the outside wheelpath of test section 1002 in Massachusetts

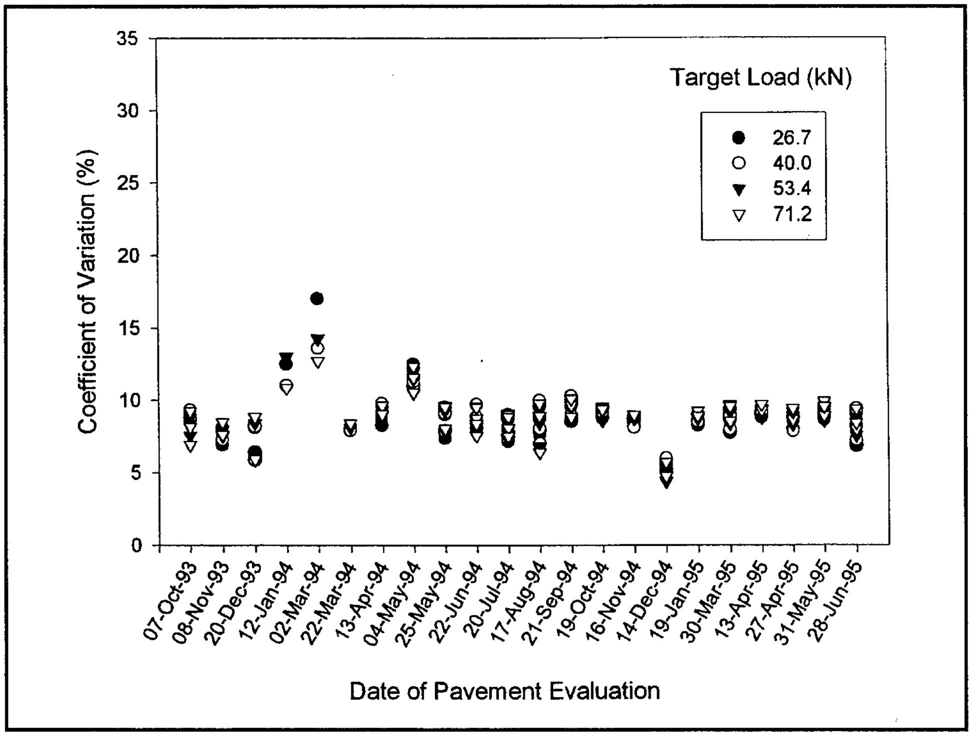


Figure D3. Variability among stations for the midlane test path of test section 1002 in Vermont

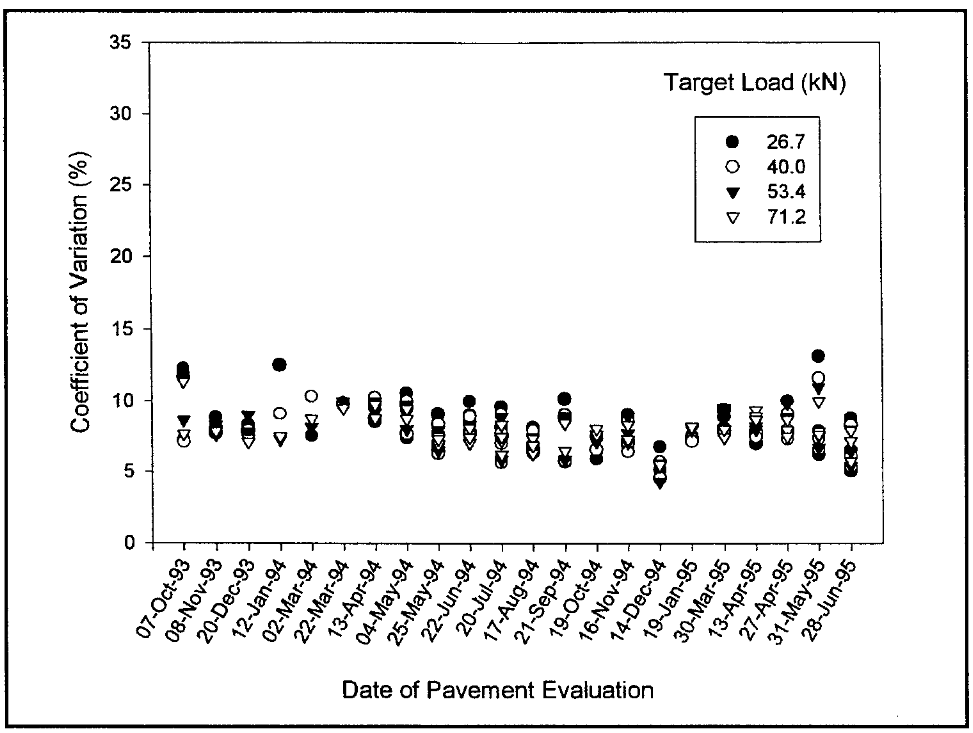


Figure D4. Variability among stations for the outside wheelpath of test section 1002 in Vermont

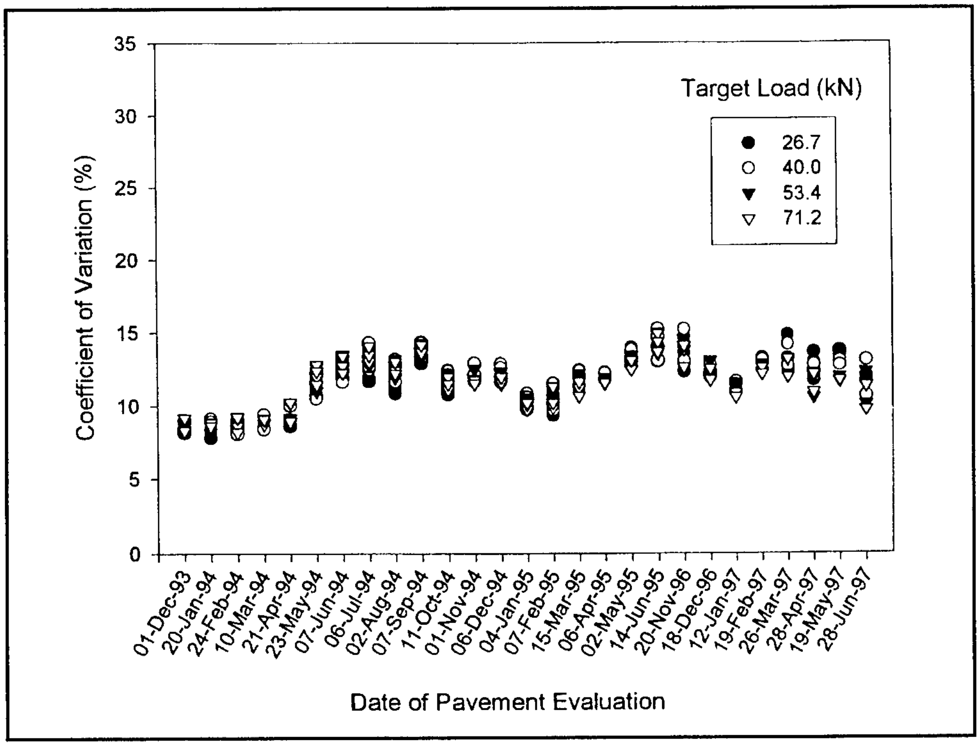


Figure D5. Variability among stations for the midlane test path of test section 1060 in Texas

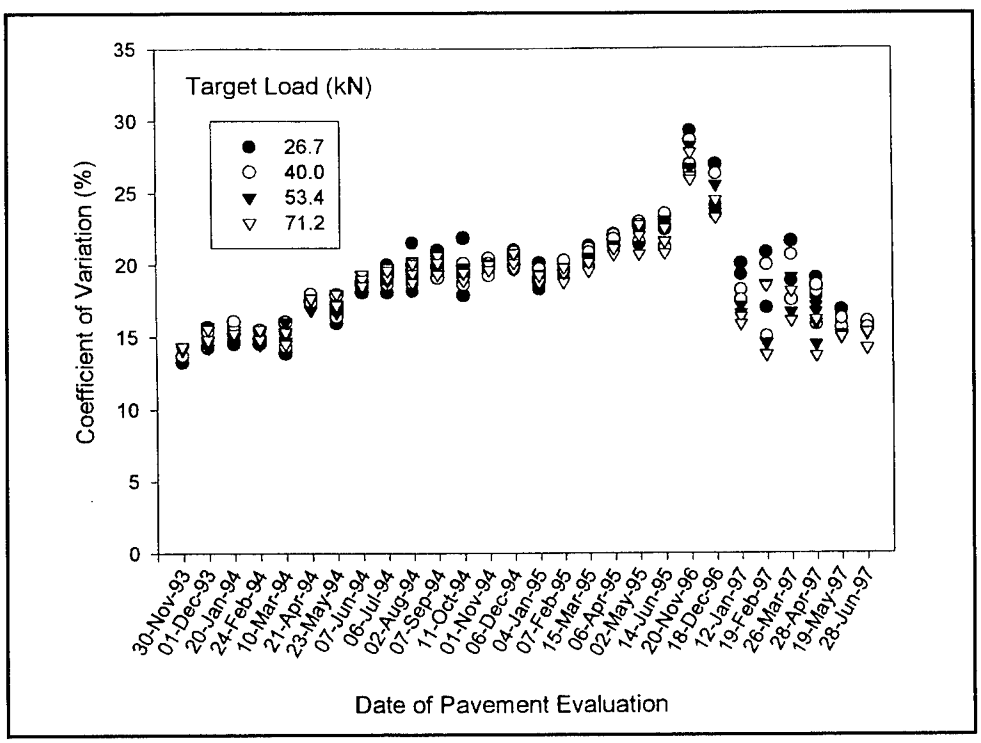


Figure D6. Variability among stations for the outside wheelpath of test section 1060 in Texas

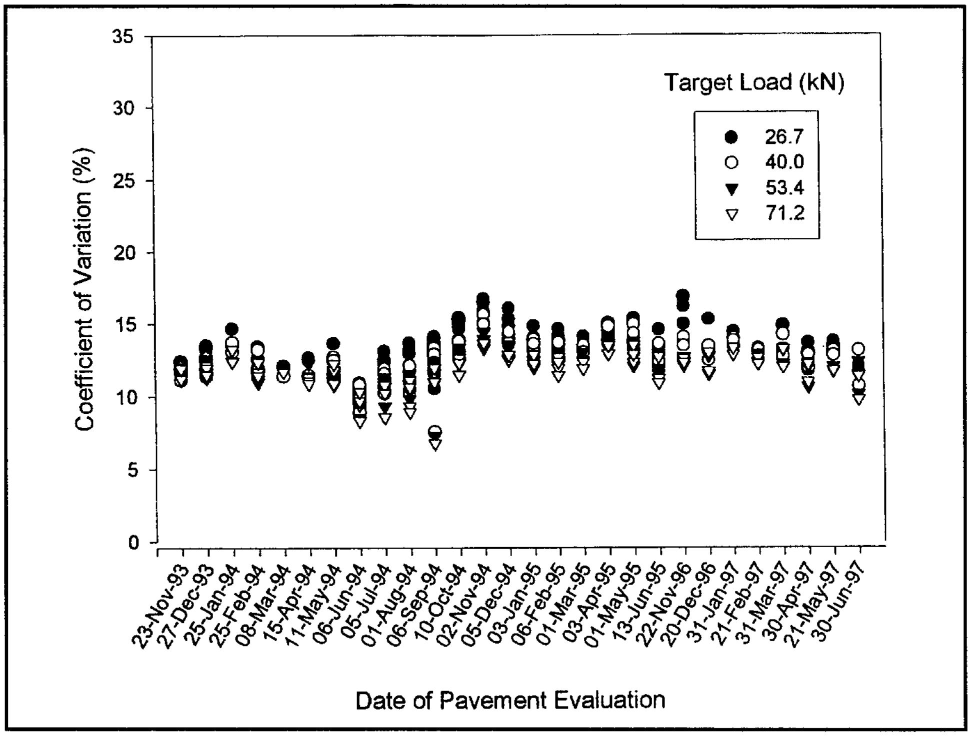


Figure D7. Variability among stations for the midlane test path of test section 1122 in Texas

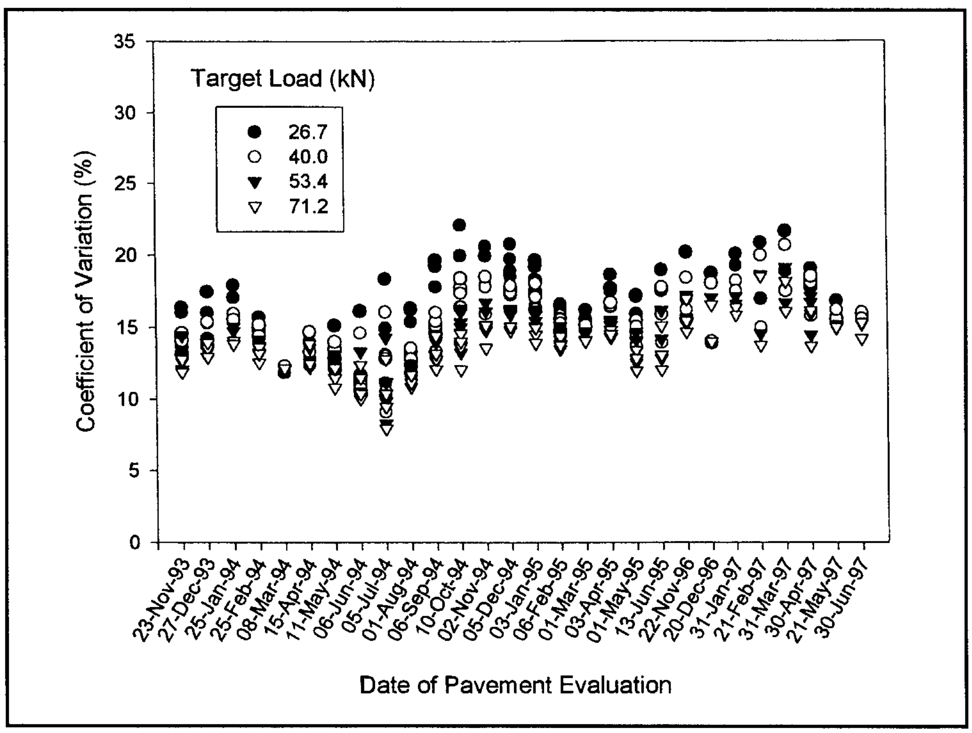


Figure D8. Variability among stations for the outside wheelpath of test section 1122 in Texas

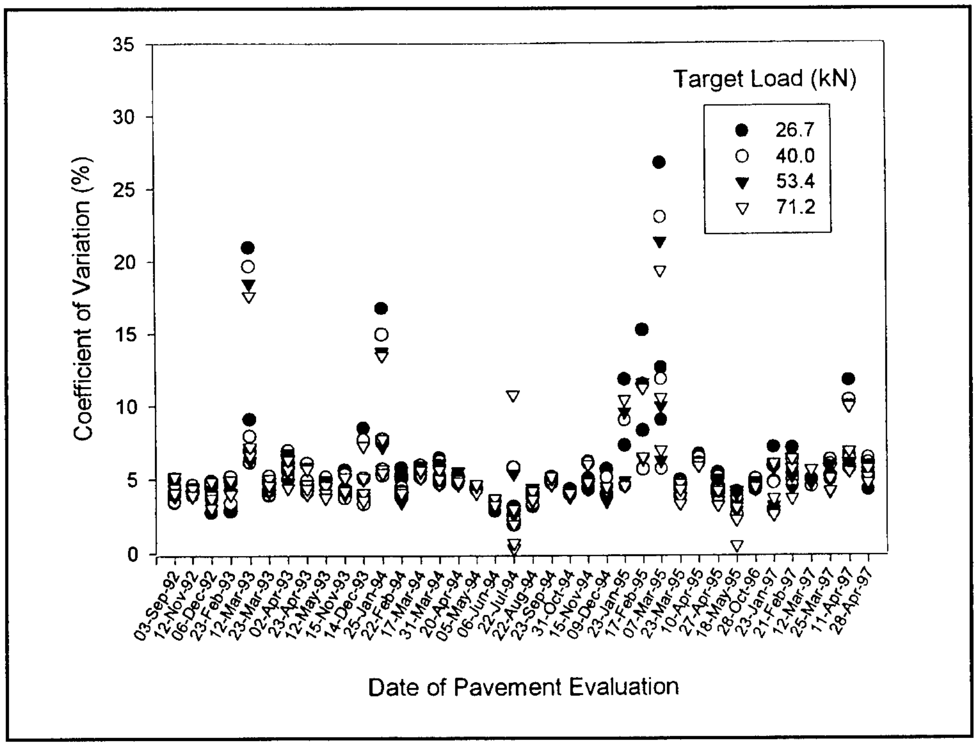


Figure D9. Variability among stations for the midlane test path of test section 8129 in Montana

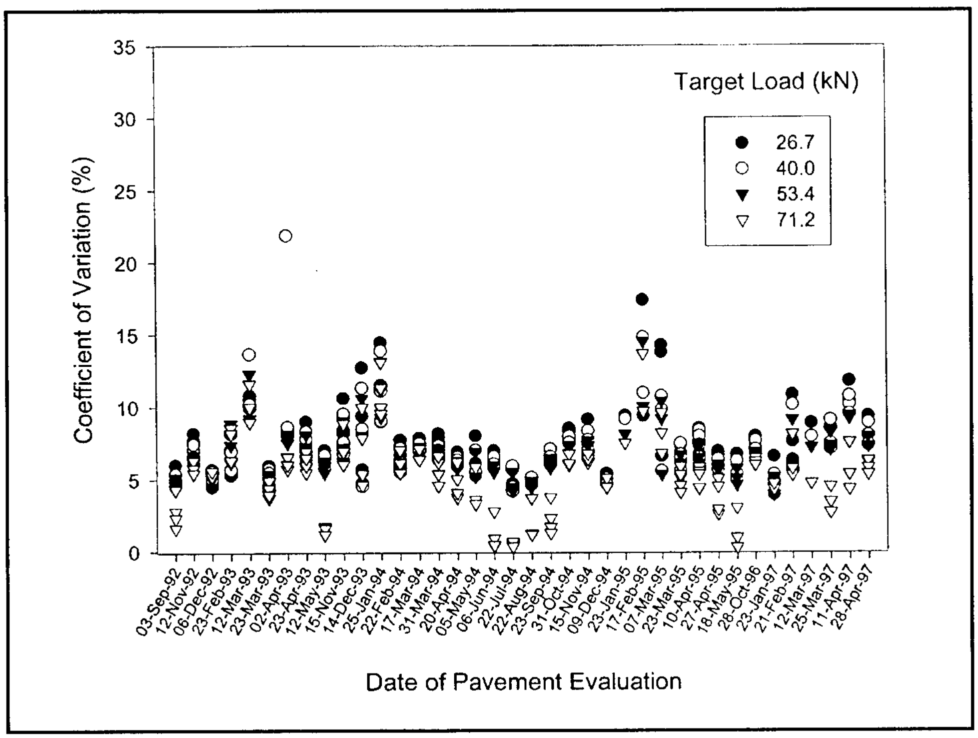


Figure D10. Variability among stations for the outside wheelpath of test section 8129 in Montana

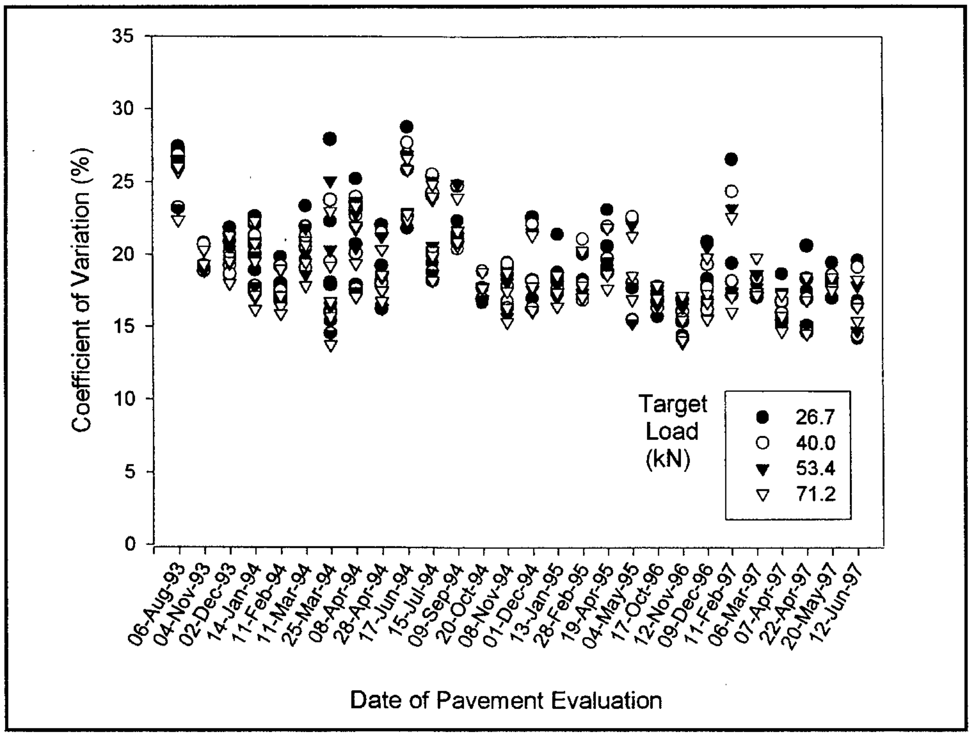


Figure D11. Variability among stations for the midlane test path of test section 1001 in Utah

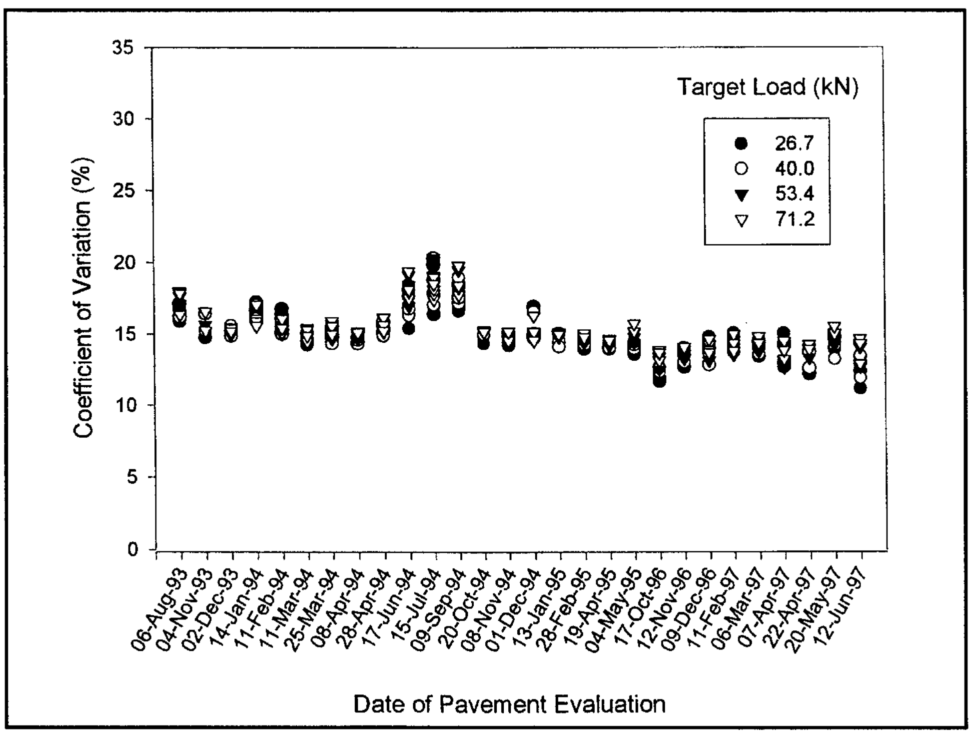


Figure D12. Variability among stations for the outside wheelpath of test section 1001 in Utah

Appendix E
Errors Caused by Increasing Station Spacing

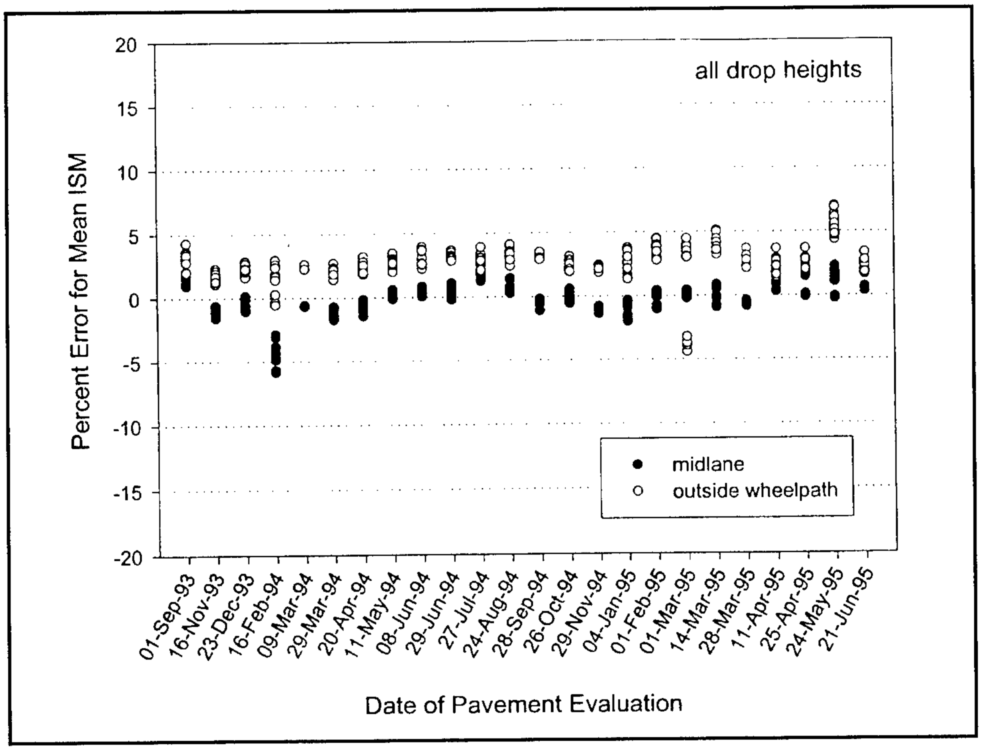


Figure E1. Errors in calculated mean ISM caused by increasing station spacing to 15.2 m (50 ft) for test section 1002 in Massachusetts

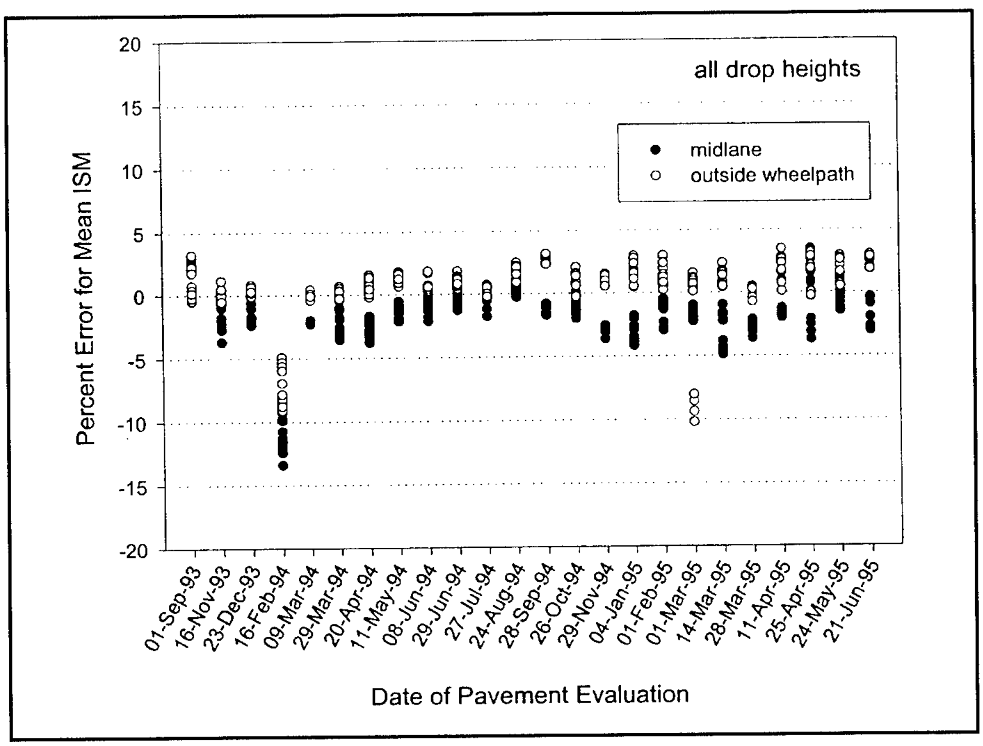


Figure E2. Errors in calculated mean ISM caused by increasing station spacing to 30.5 m (100 ft) for test section 1002 in Massachusetts

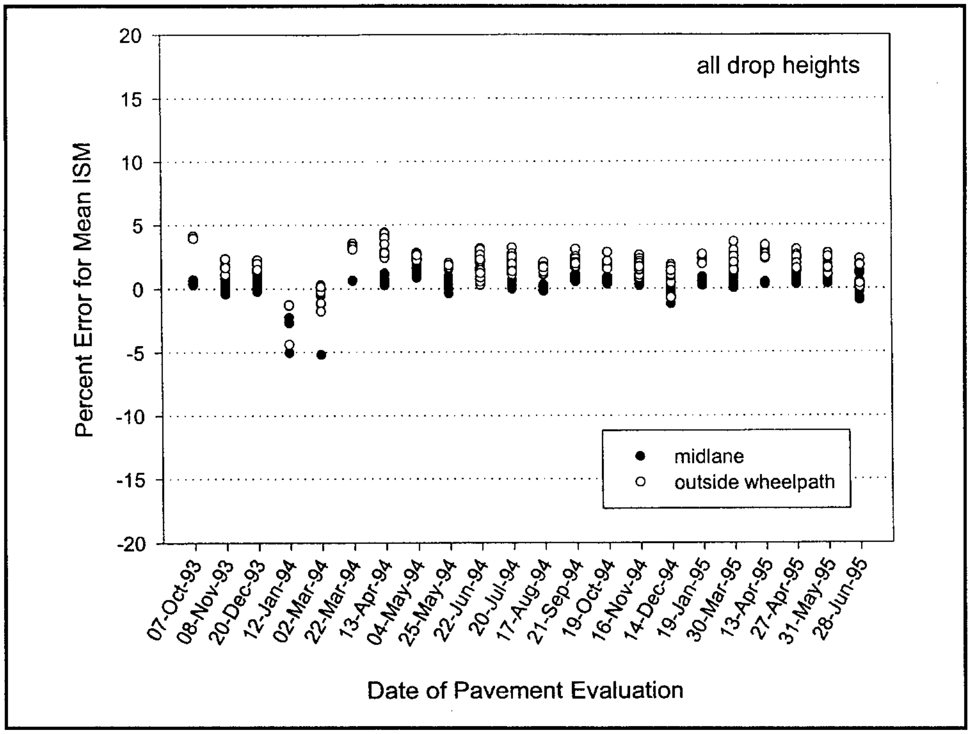


Figure E3. Errors in calculated mean ISM caused by increasing station spacing to 15.2 m (50 ft) for test section 1002 in Vermont

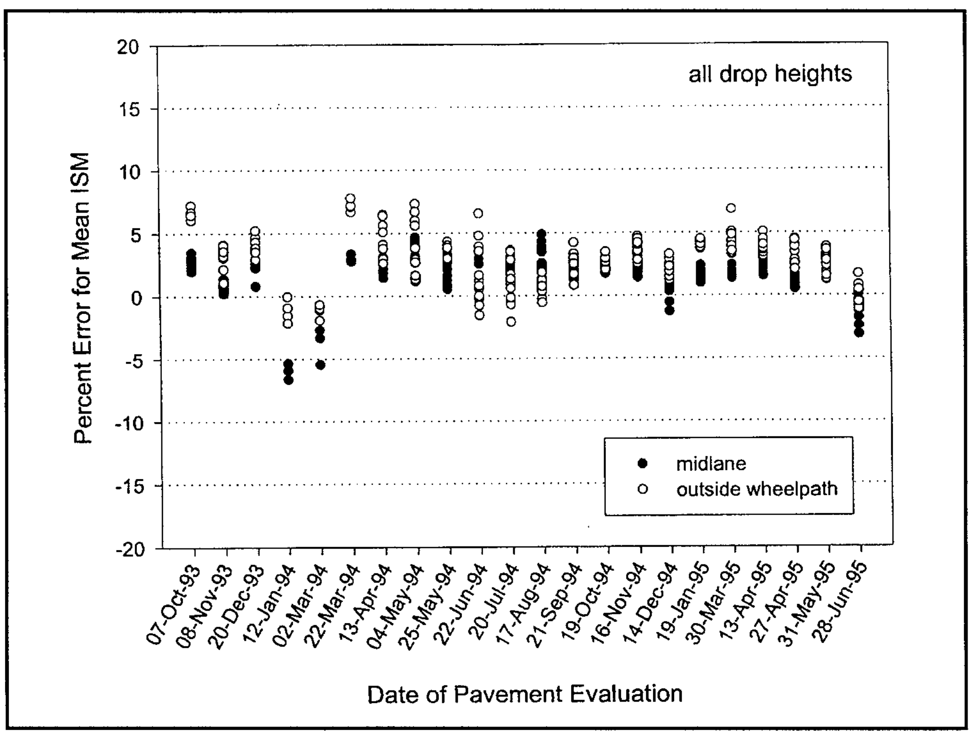


Figure E4. Errors in calculated mean ISM caused by increasing station spacing to 30.5 m (100 ft) for test section 1002 in Vermont

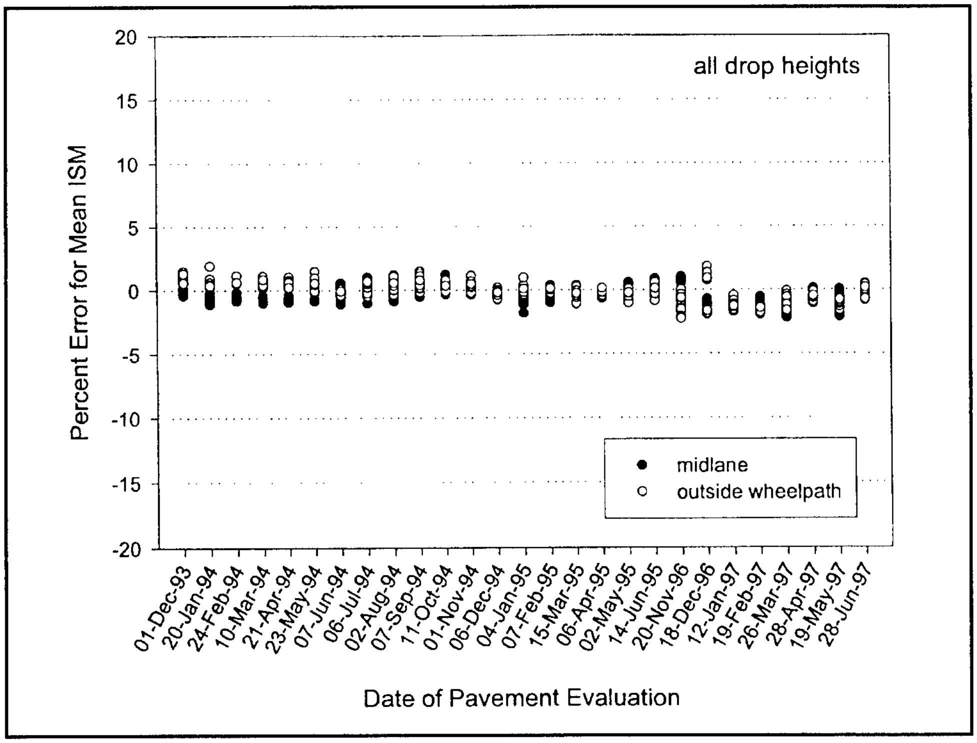


Figure E5. Errors in calculated mean ISM caused by increasing station spacing to 15.2 m (50 ft) for test section 1060 in Texas

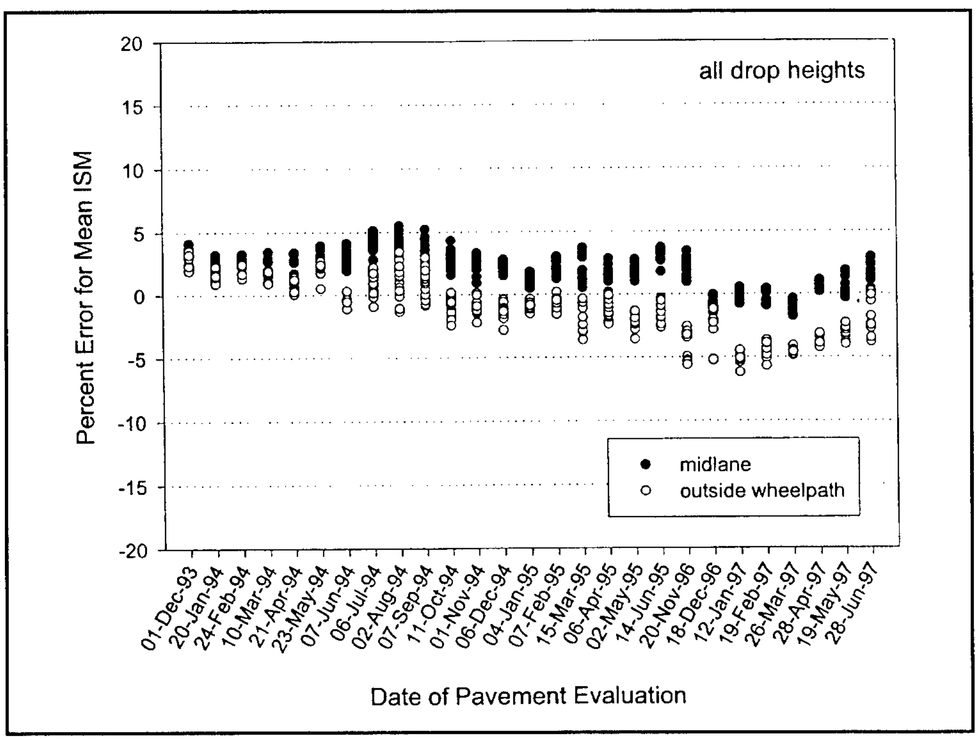


Figure E6. Errors in calculated mean ISM caused by increasing station spacing to 30.5 m (100 ft) for test section 1060 in Texas

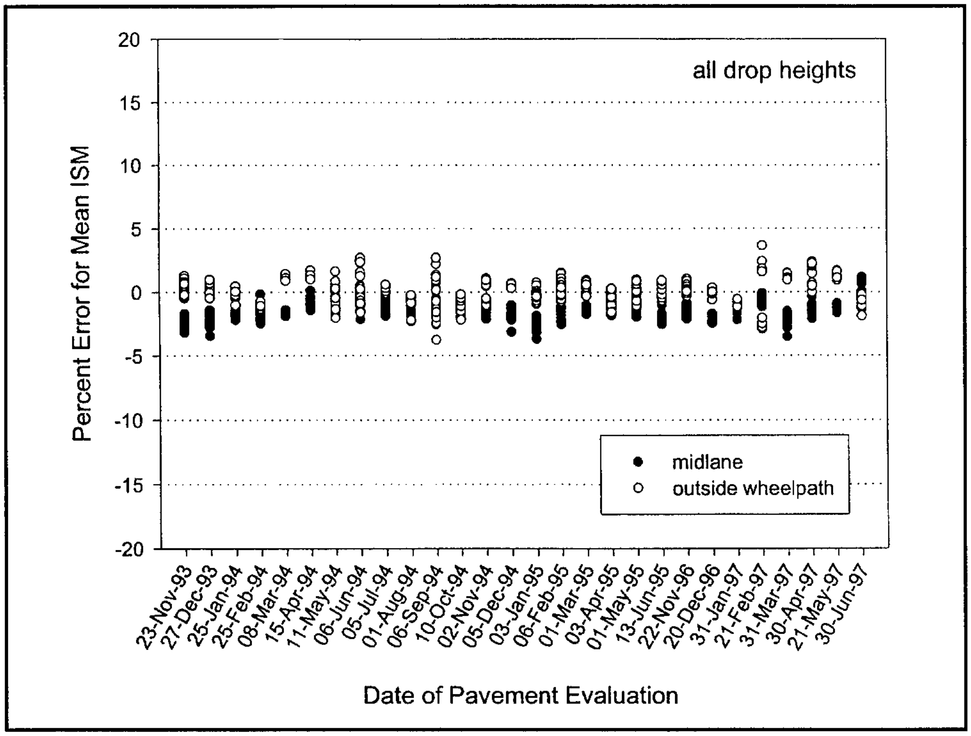


Figure E7. Errors in calculated mean ISM caused by increasing station spacing to 15.2 m (50 ft) for test section 1122 in Texas

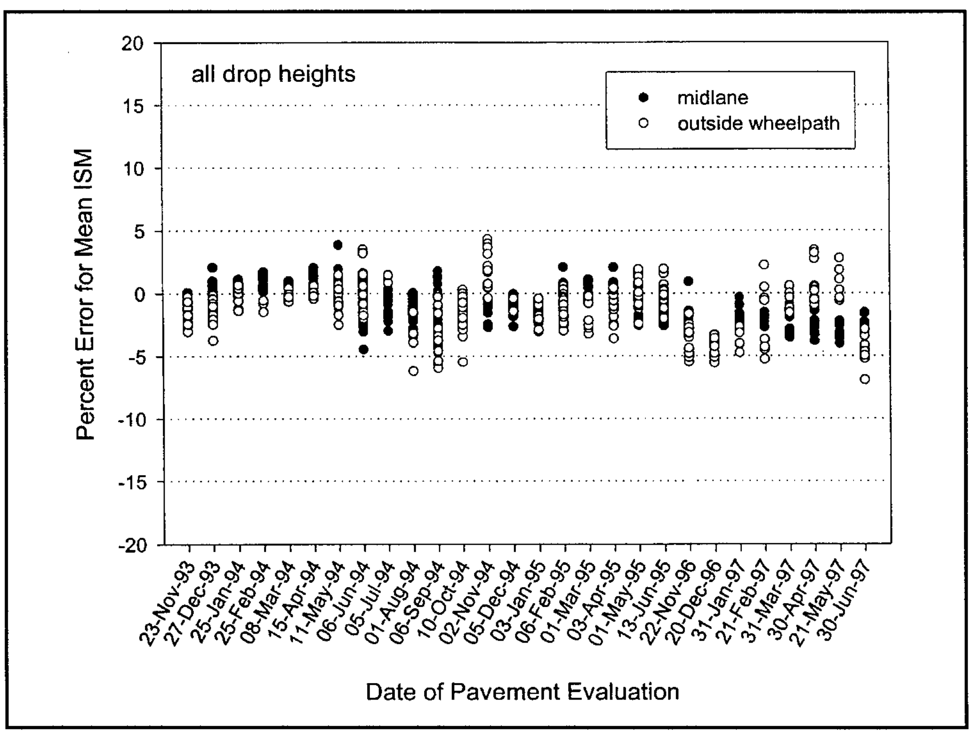


Figure E8. Errors in calculated mean ISM caused by increasing station spacing to 30.5 m (100 ft) for test section 1122 in Texas

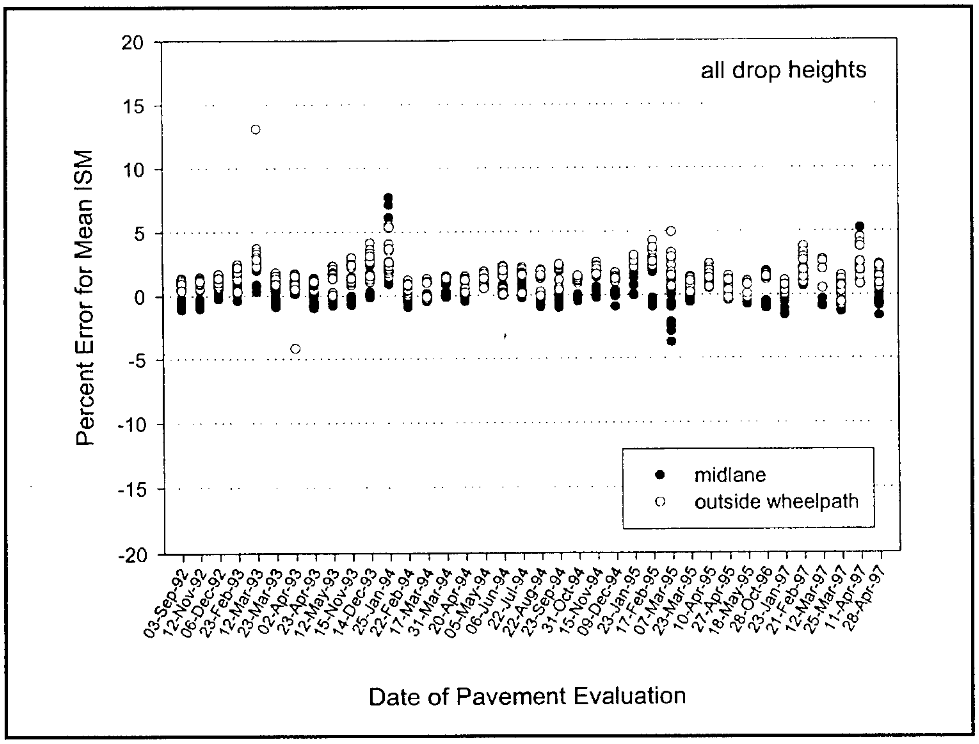


Figure E9. Errors in calculated mean ISM caused by increasing station spacing to 15.2 m (50 ft) for test section 8129 in Montana

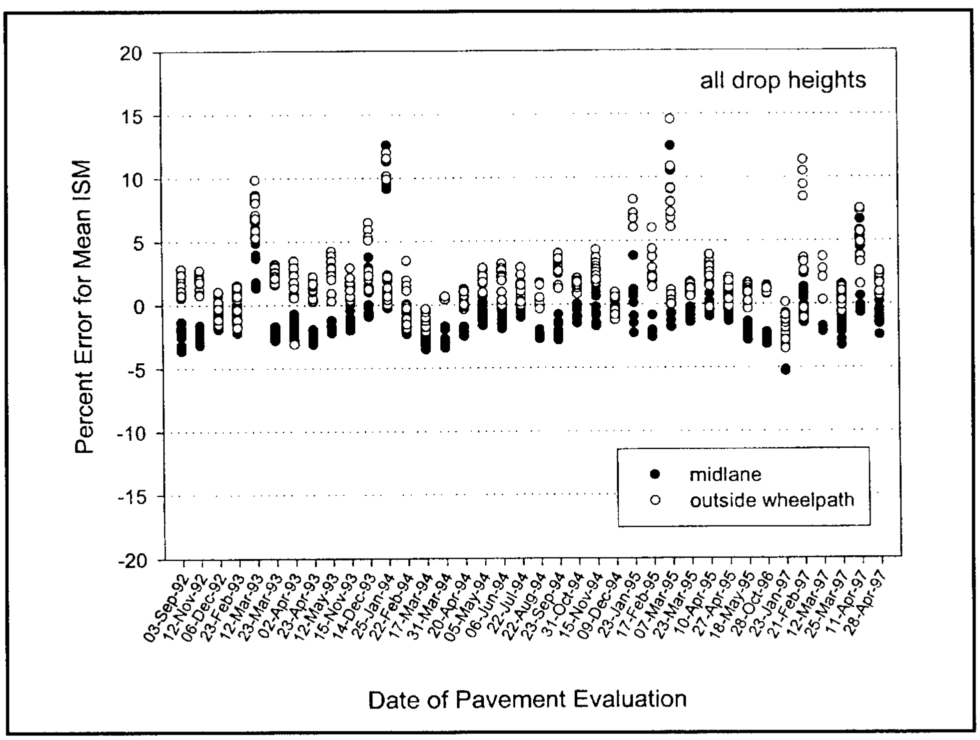


Figure E10. Errors in calculated mean ISM caused by increasing station spacing to 30.5 m (100 ft) for test section 8129 in Montana

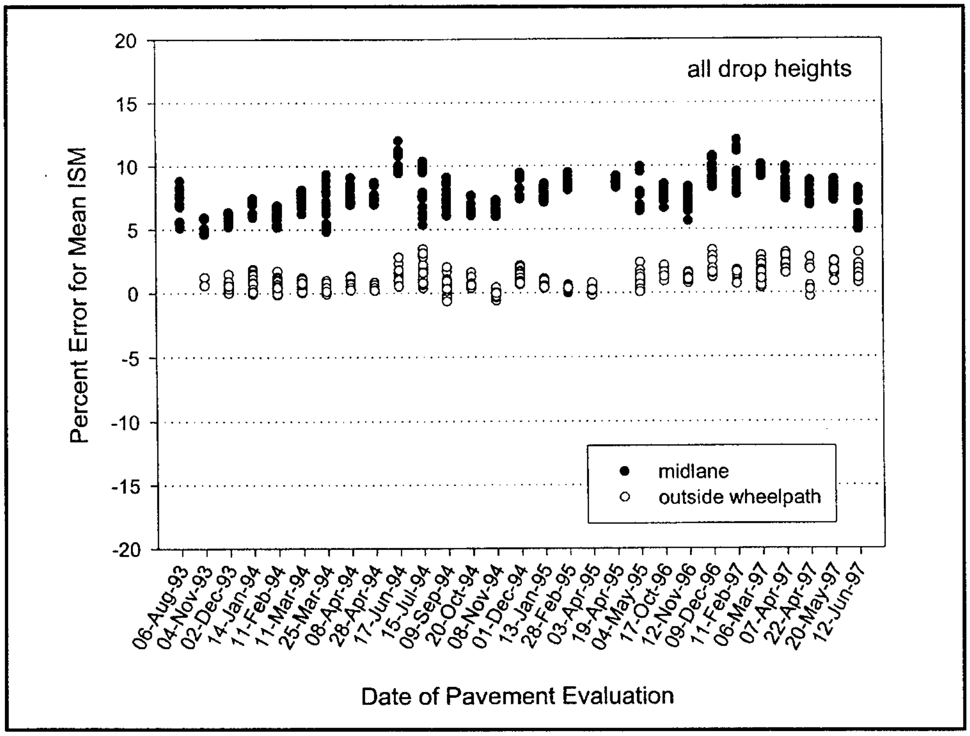


Figure E11. Errors in calculated mean ISM caused by increasing station spacing to 15.2 m (50 ft) for test section 1001 in Utah

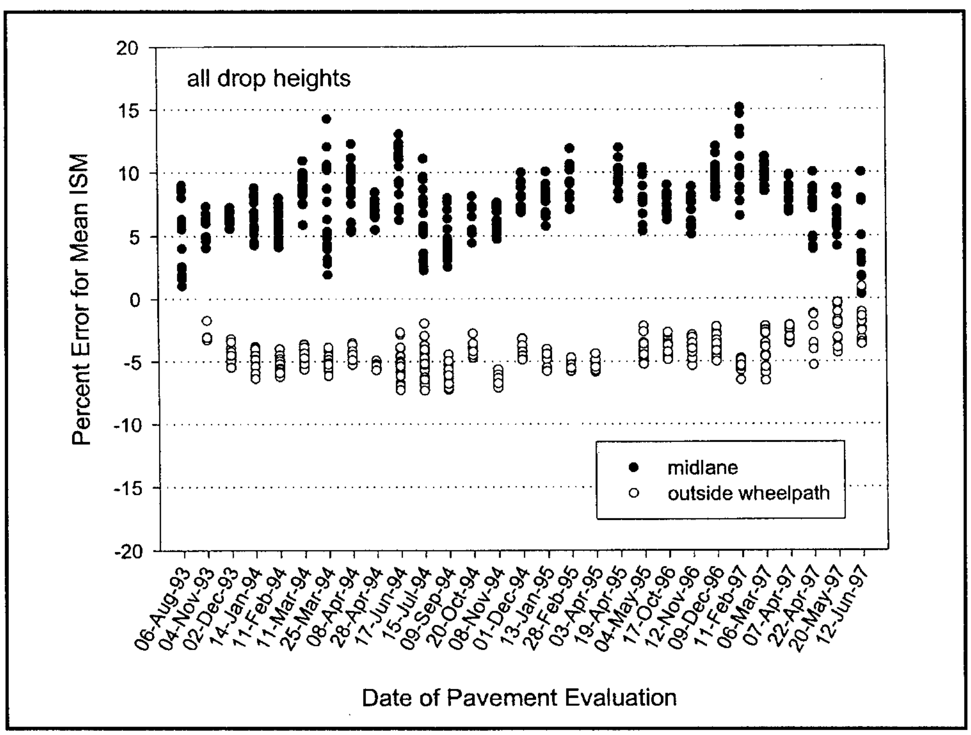


Figure E12. Errors in calculated mean ISM caused by increasing station spacing to 30.5 m (100 ft) for test section 1001 in Utah

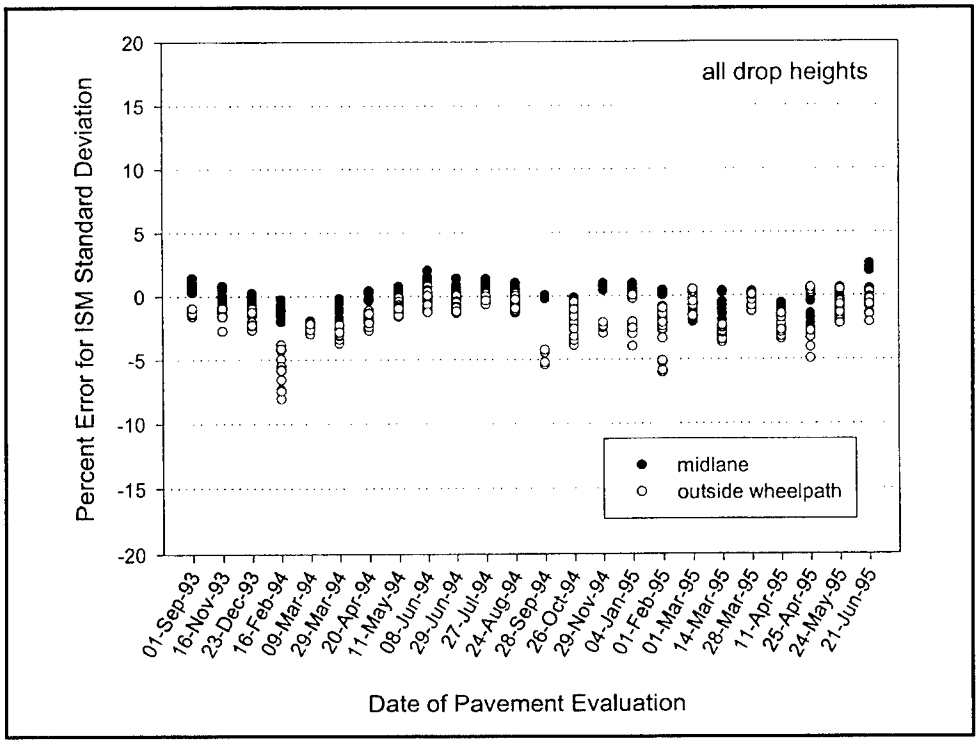


Figure E13. Errors in calculated ISM variability caused by increasing station spacing to 15.2 m (50 ft) for test section 1002 in Massachusetts

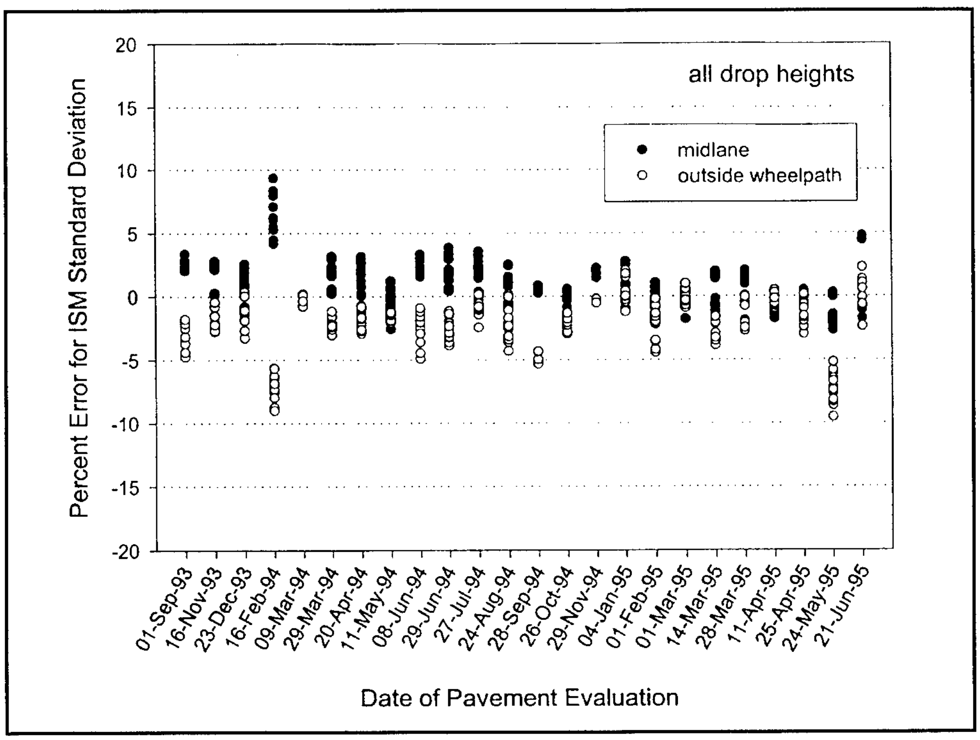


Figure E14. Errors in calculated ISM variability caused by increasing station spacing to 30.5 m (100 ft) for test section 1002 in Massachusetts

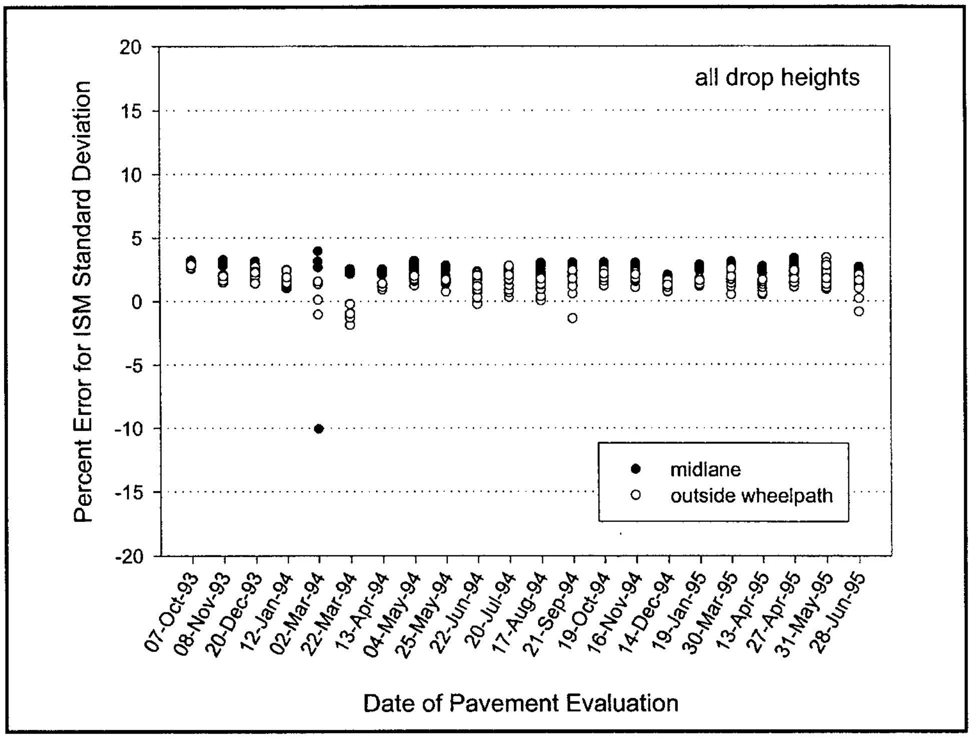


Figure E15. Errors in calculated ISM variability caused by increasing station spacing to 15.2 m (50 ft) for test section 1002 in Vermont

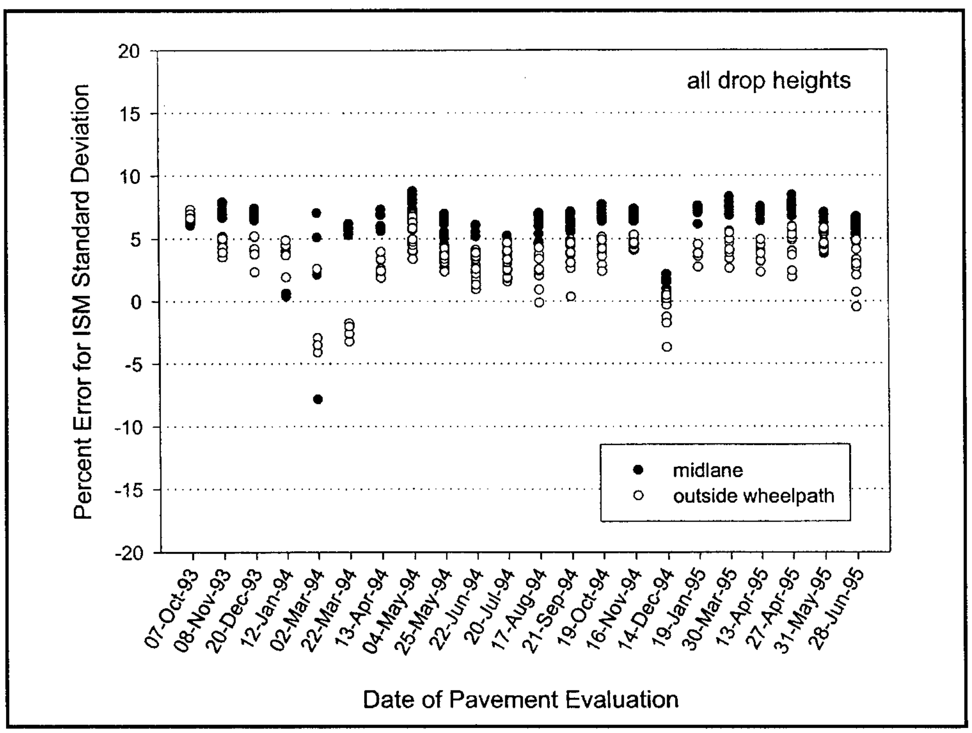


Figure E16. Errors in calculated ISM variability caused by increasing station spacing to 30.5 m (100 ft) for test section 1002 in Vermont

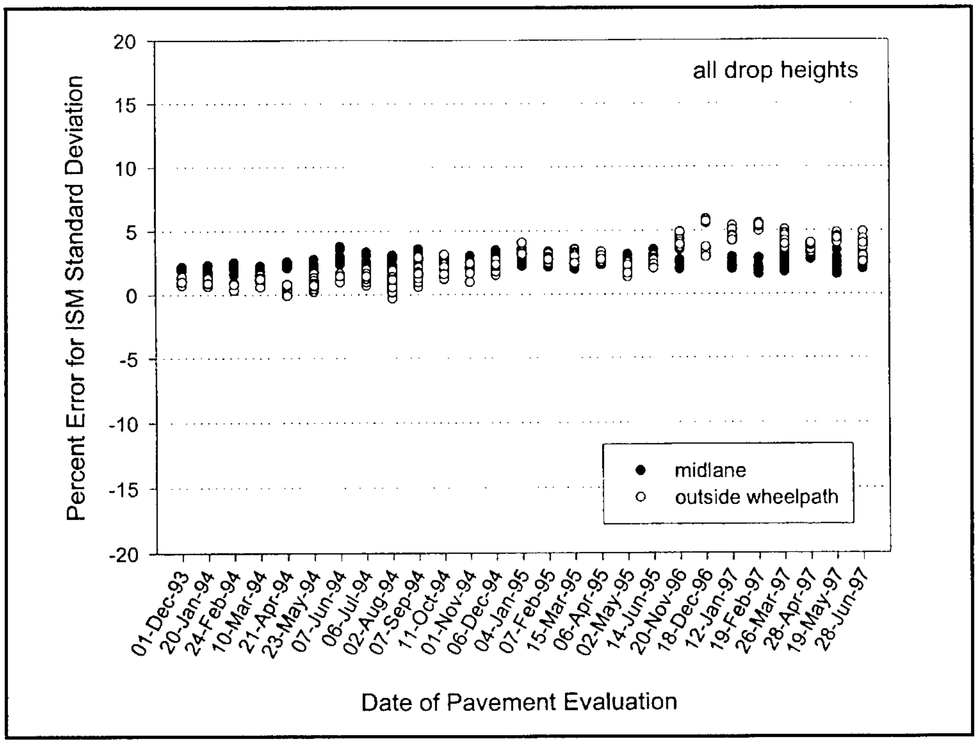


Figure E17. Errors in calculated ISM variability caused by increasing station spacing to 15.2 m (50 ft) for test section 1060 in Texas

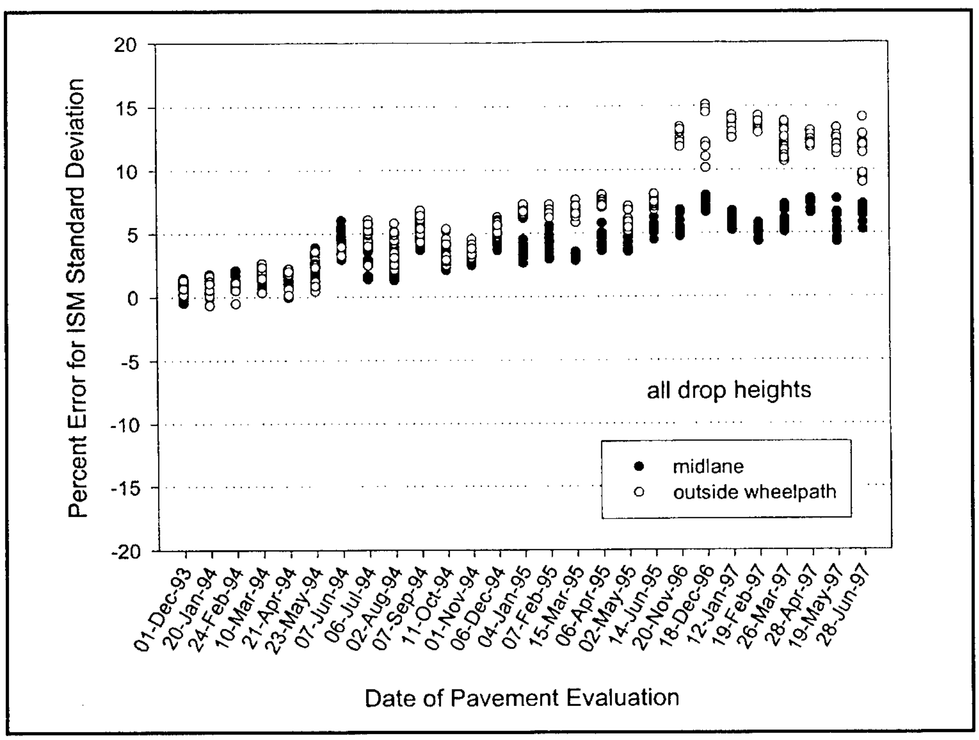


Figure E18. Errors in calculated ISM variability caused by increasing station spacing to 30.5 m (100 ft) for test section 1060 in Texas

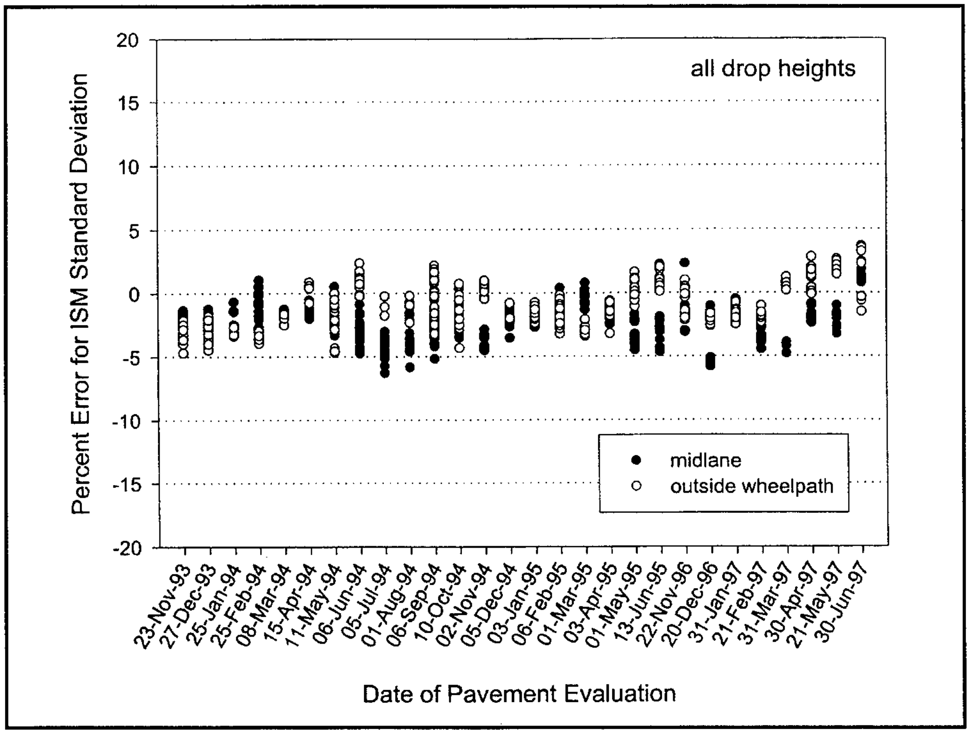


Figure E19. Errors in calculated ISM variability caused by increasing station spacing to 15.2 m (50 ft) for test section 1122 in Texas

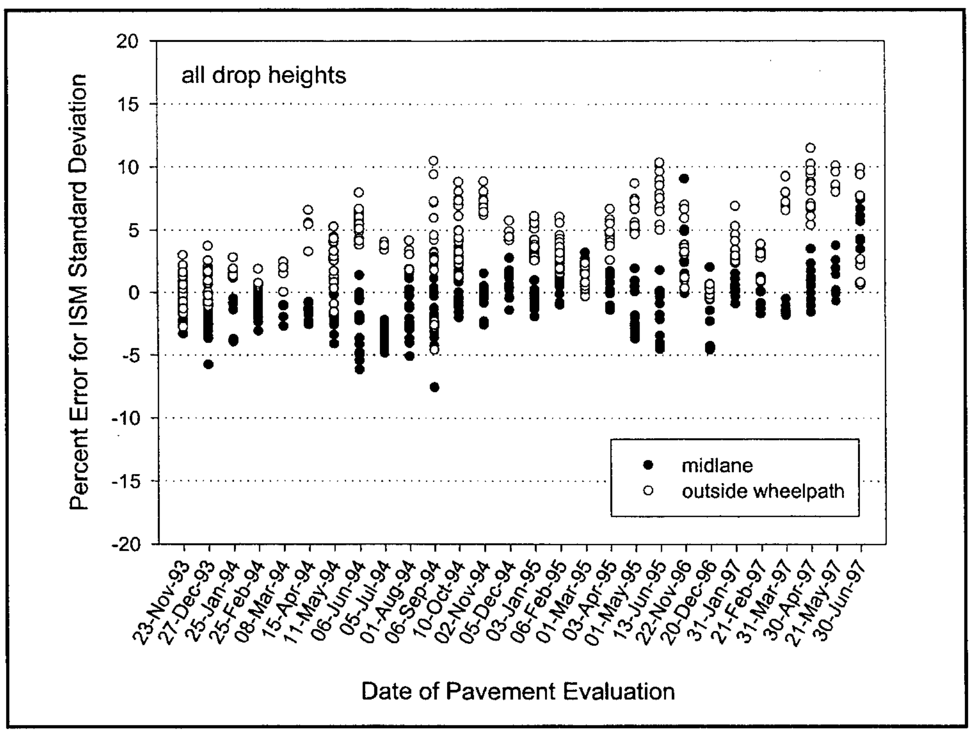


Figure E20. Errors in calculated ISM variability caused by increasing station spacing to 30.5 m (100 ft) for test section 1122 in Texas

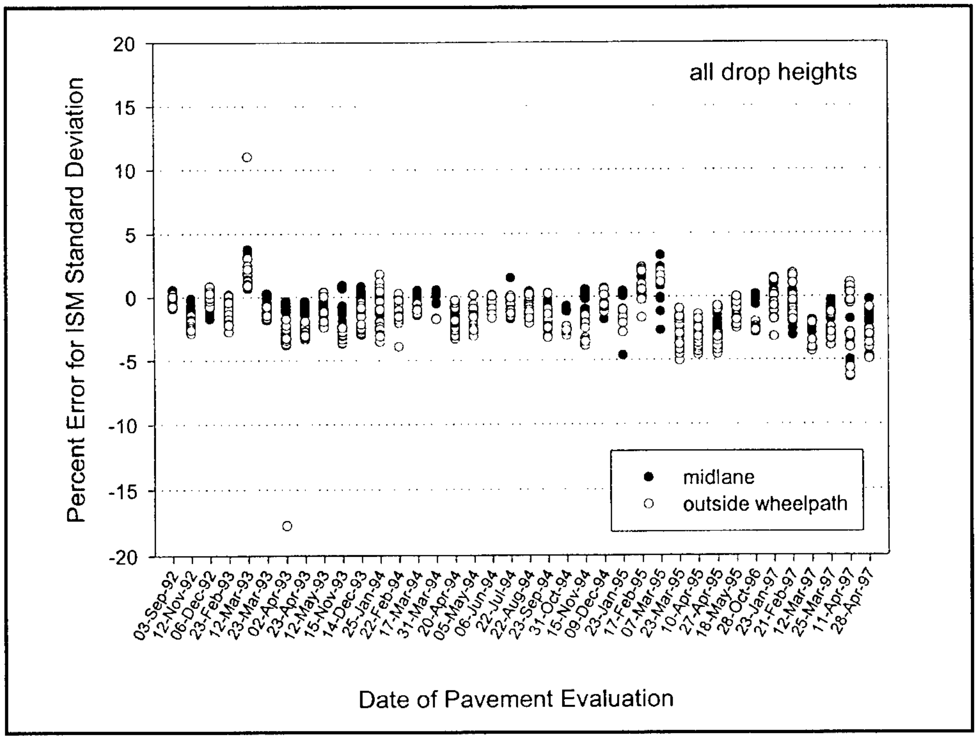


Figure E21. Errors in calculated ISM variability caused by increasing station spacing to 15.2 m (50 ft) for test section 8129 in Montana

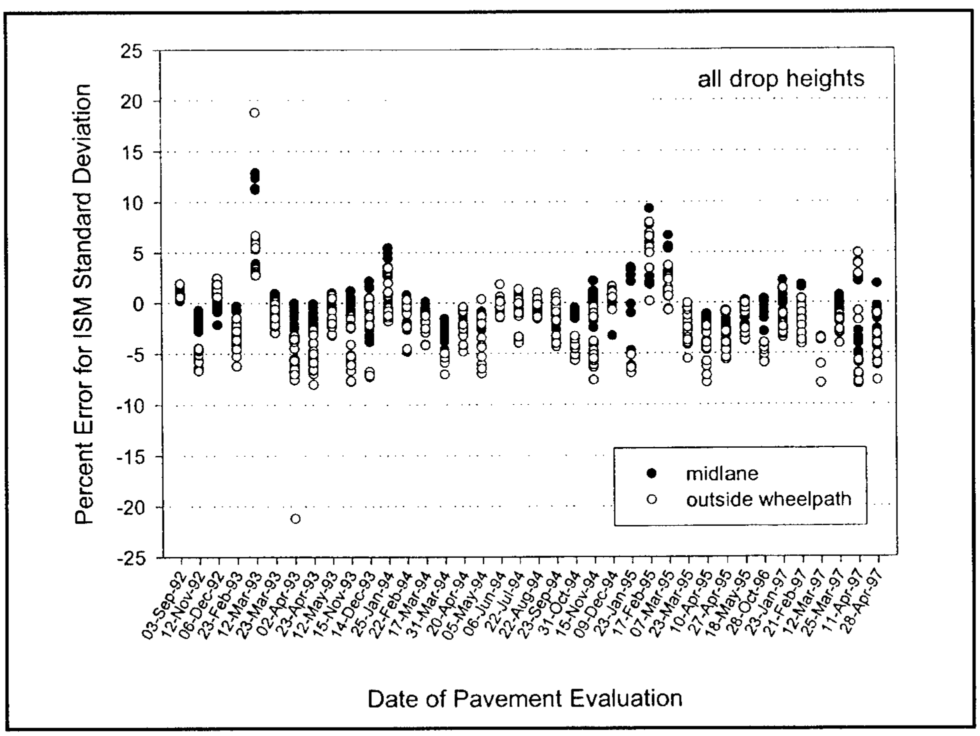


Figure E22. Errors in calculated ISM variability caused by increasing station spacing to 30.5 m (100 ft) for test section 8129 in Montana

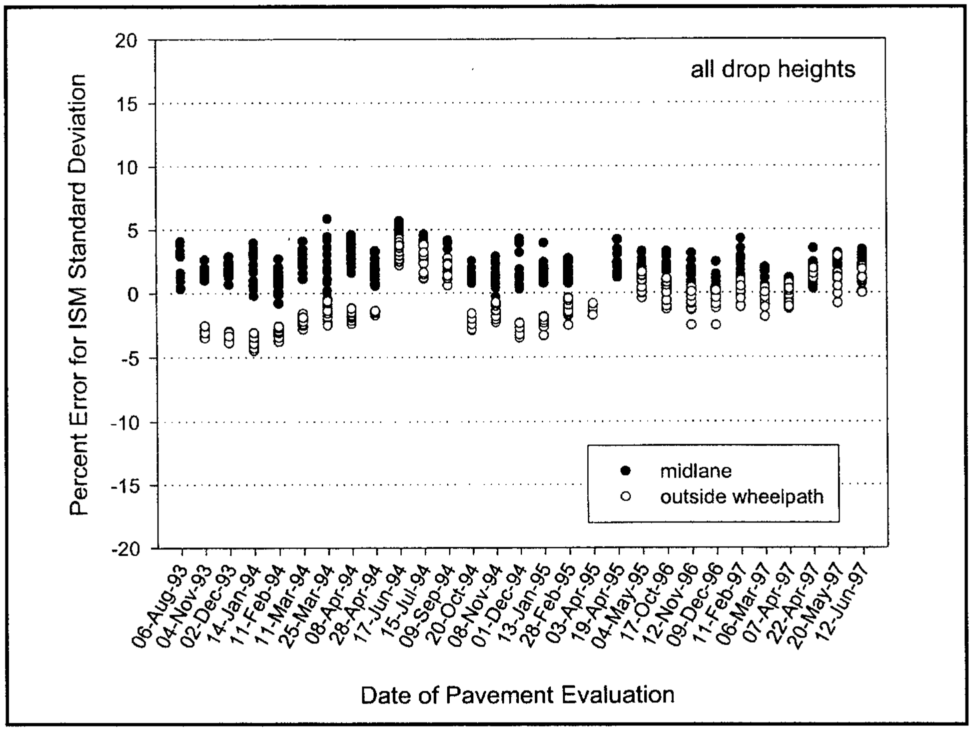


Figure E23. Errors in calculated ISM variability caused by increasing station spacing to 15.2 m (50 ft) for test section 1001 in Utah

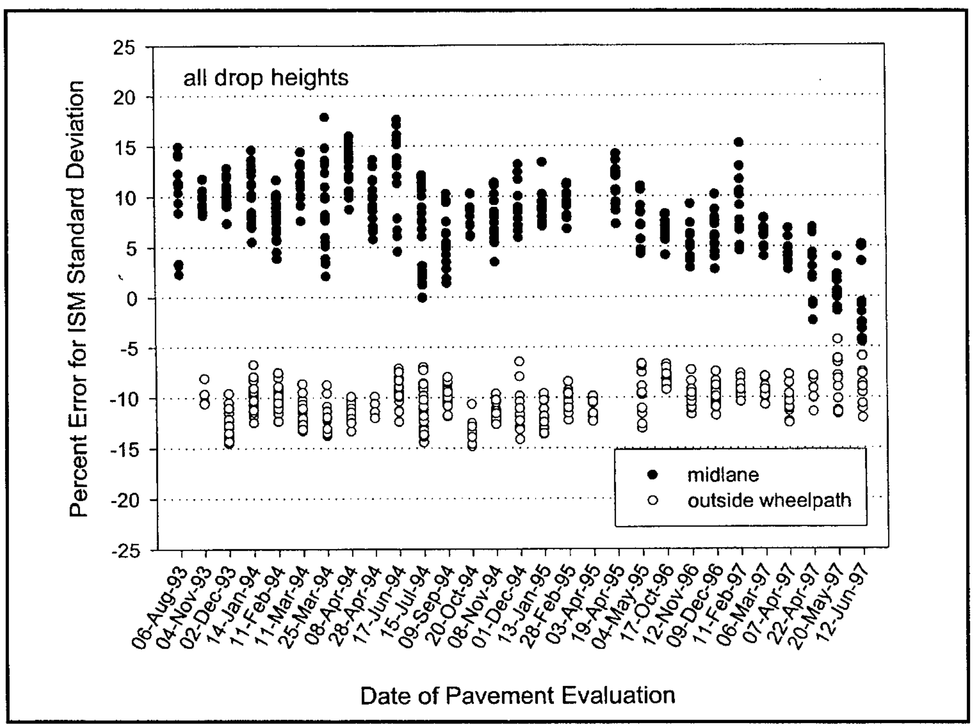


Figure E24. Errors in calculated ISM variability caused by increasing station spacing to 30.5 m (100 ft) for test section 1001 in Utah

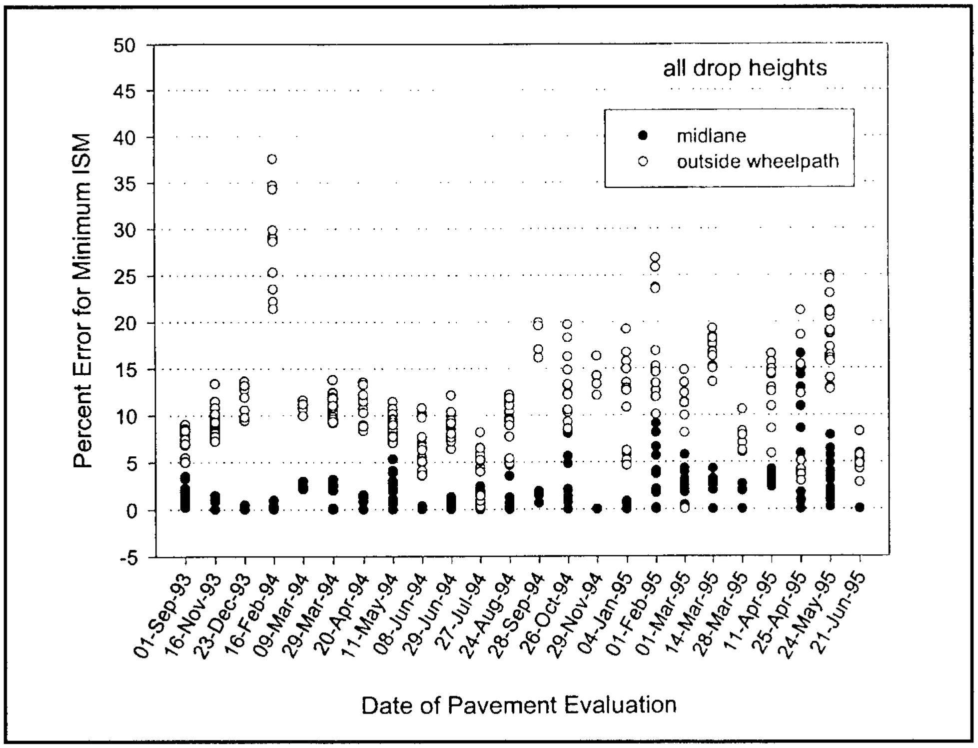
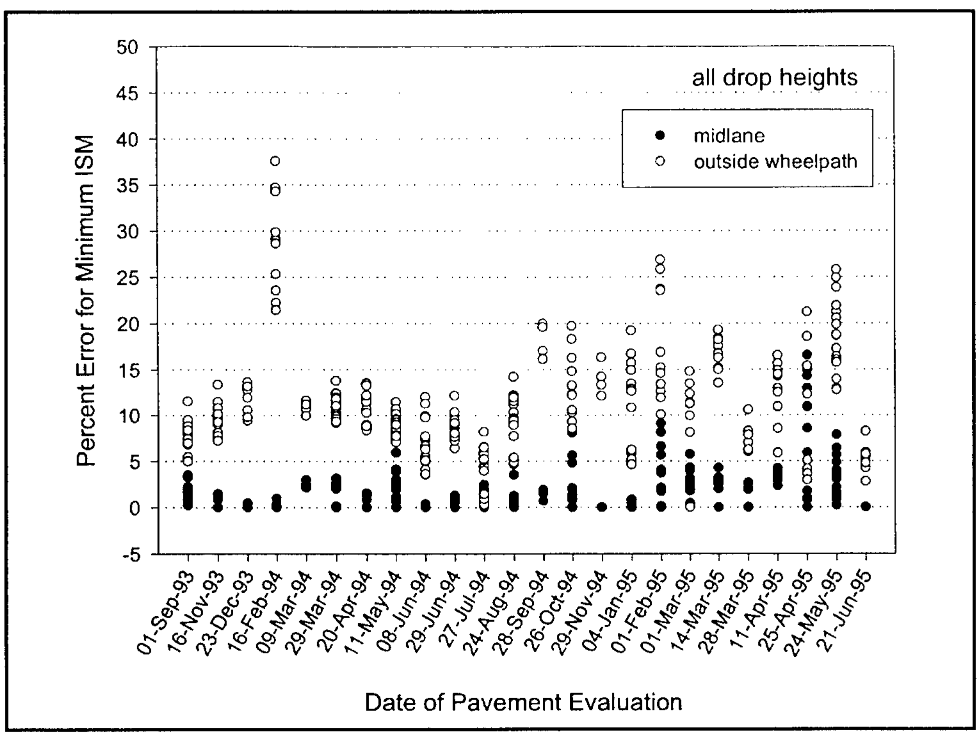


Figure E25. Errors in estimated minimum ISM caused by increasing station spacing to 15.2 m (50 ft) for test section 1002 in Massachusetts



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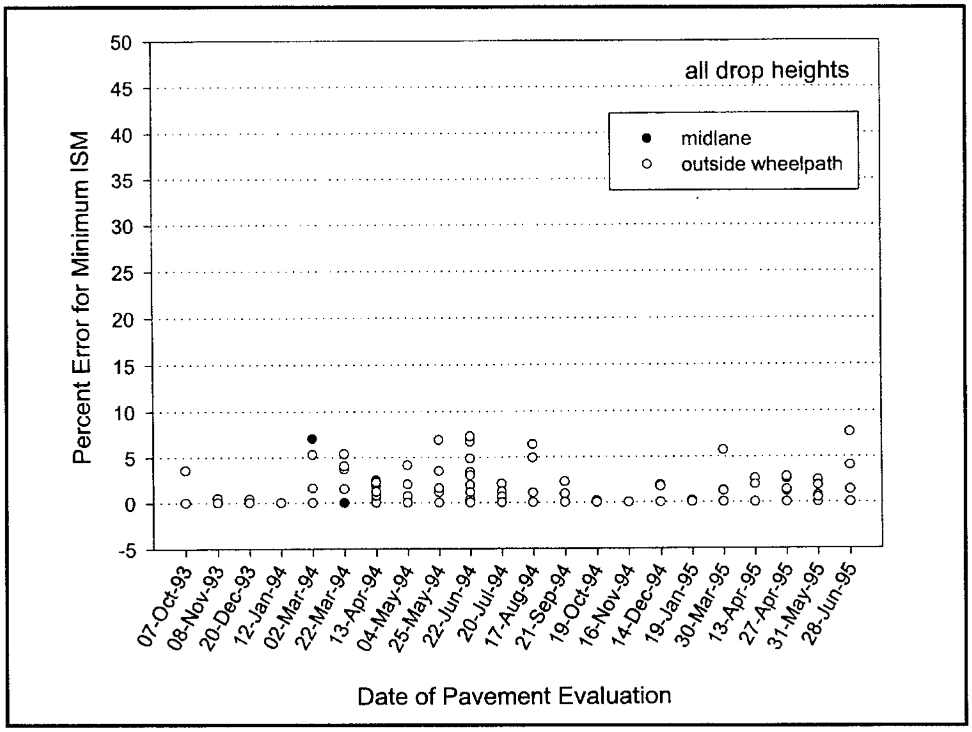


Figure E27. Errors in estimated minimum ISM caused by increasing station spacing to 15.2 m (50 ft) for test section 1002 in Vermont

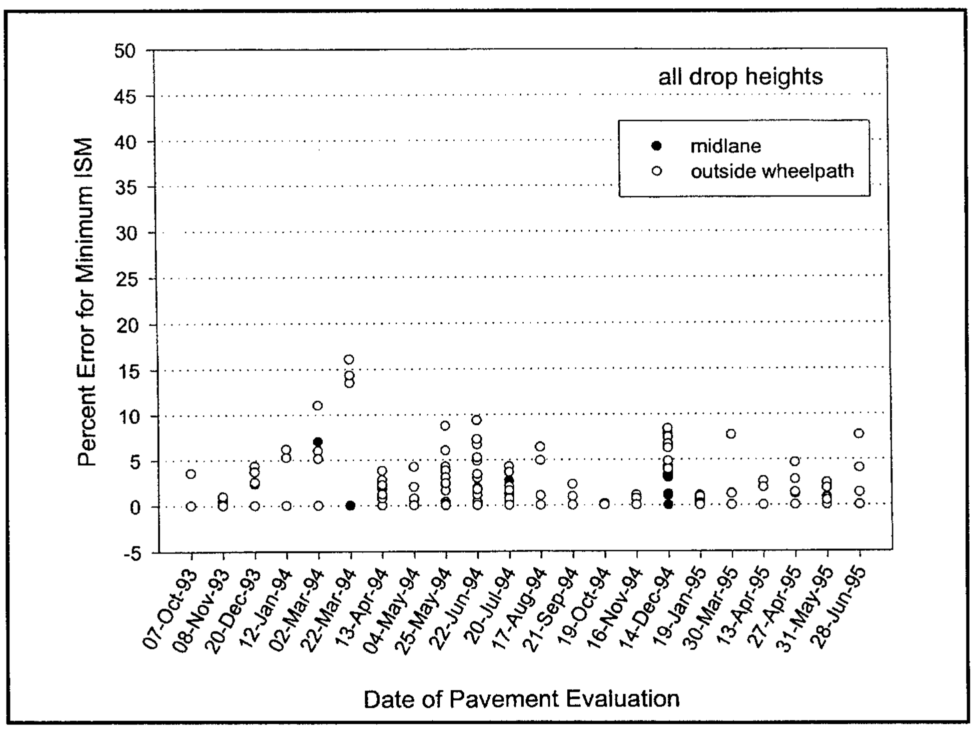


Figure E28. Errors in estimated minimum ISM caused by increasing station spacing to 30.5 m (100 ft) for test section 1002 in Vermont

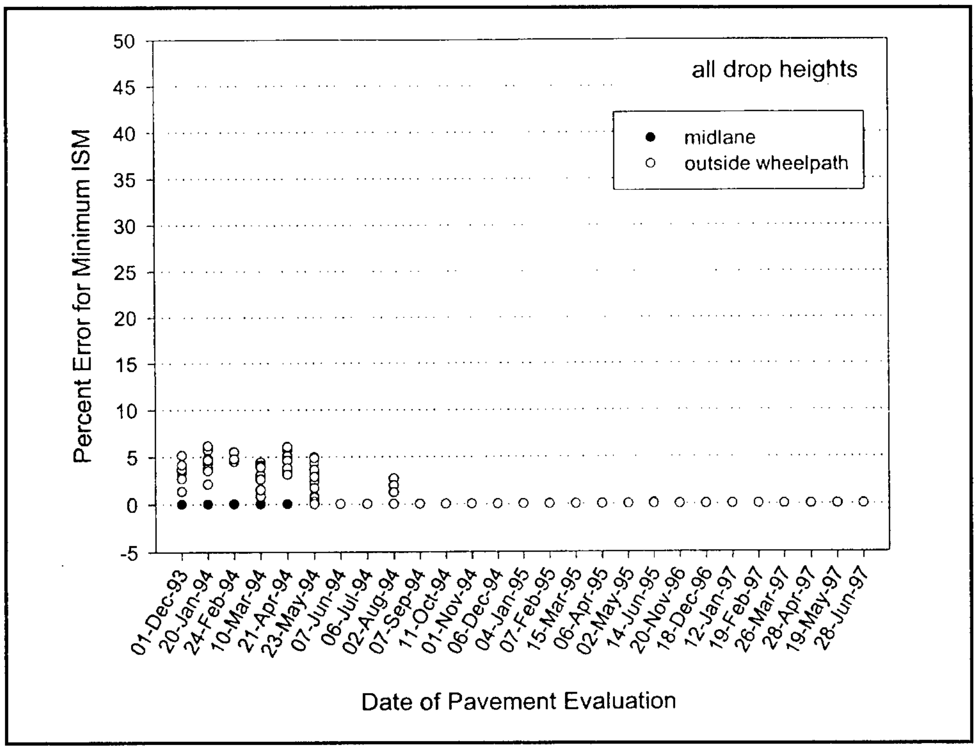


Figure E29. Errors in estimated minimum ISM caused by increasing station spacing to 15.2 m (50 ft) for test section 1060 in Texas

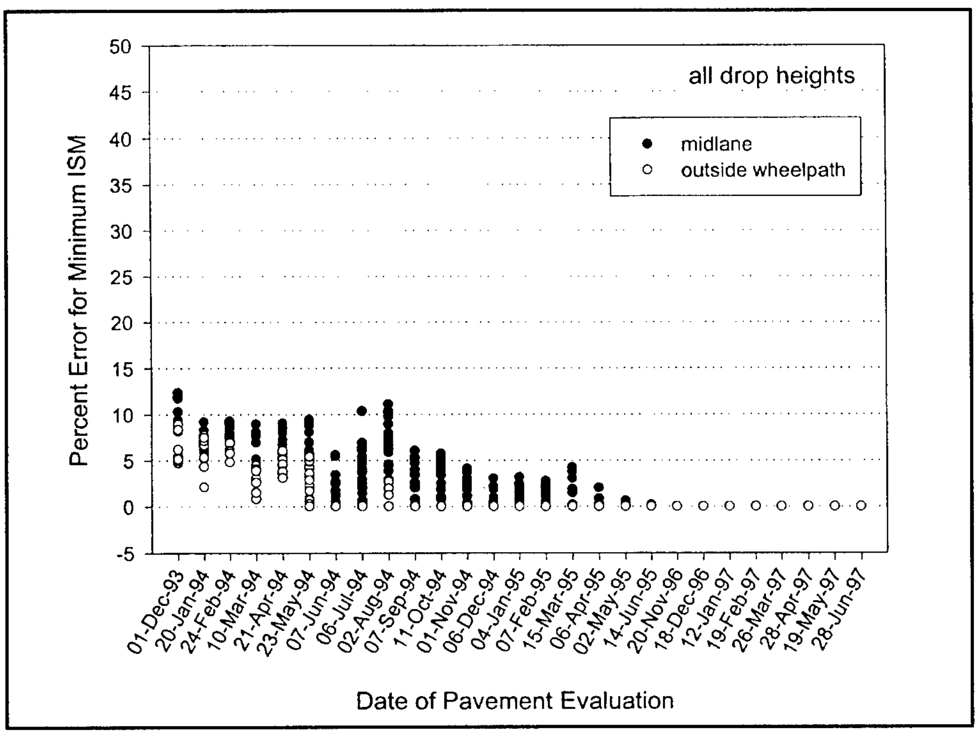


Figure E30. Errors in estimated minimum ISM caused by increasing station spacing to 30.5 m (100 ft) for test section 1060 in Texas

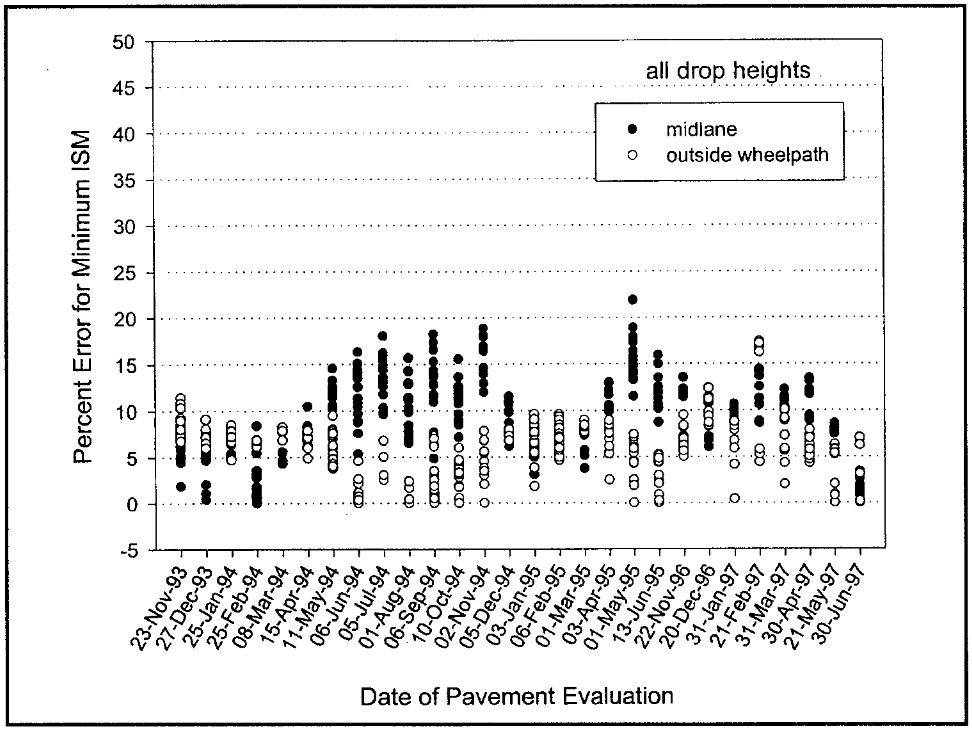


Figure E31. Errors in estimated minimum ISM caused by increasing station spacing to 15.2 m (50 ft) for test section 1122 in Texas

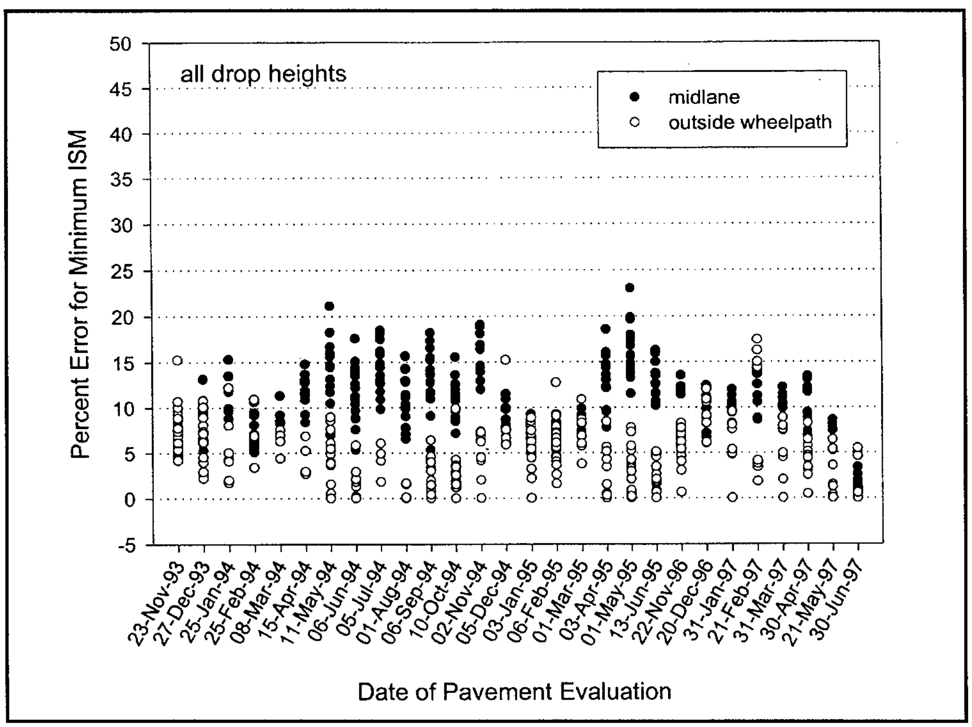


Figure E32. Errors in estimated minimum ISM caused by increasing station spacing to 30.5 m (100 ft) for test section 1122 in Texas

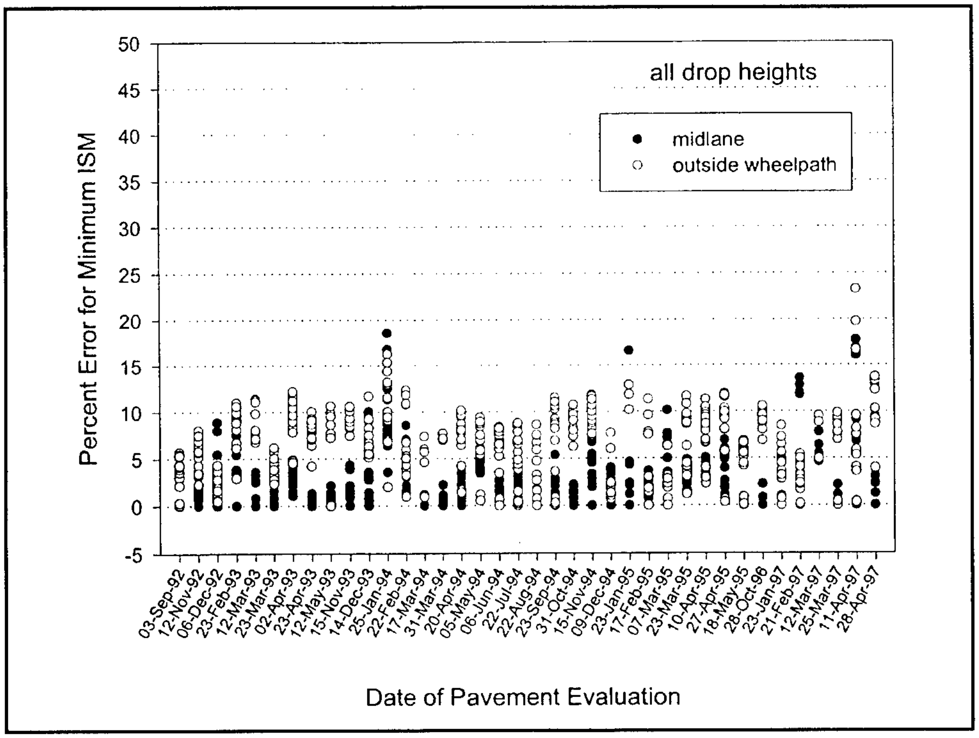


Figure E33. Errors in estimated minimum ISM caused by increasing station spacing to 15.2 m (50 ft) for test section 8129 in Montana

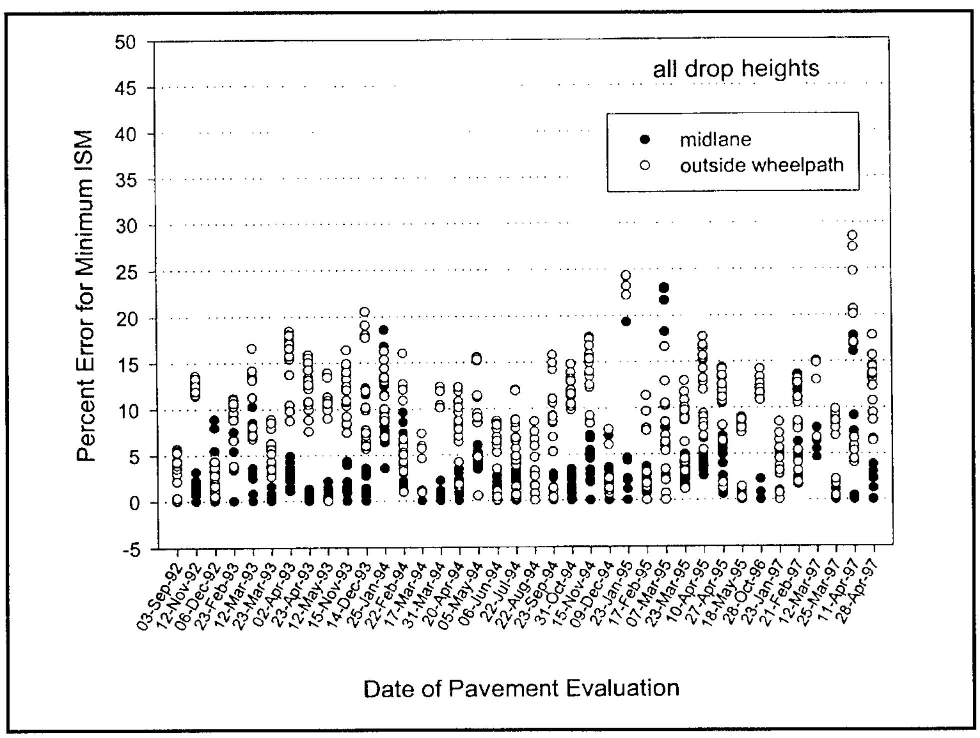


Figure E34. Errors in estimated minimum ISM caused by increasing station spacing to 30.5 m (100 ft) for test section 8129 in Montana

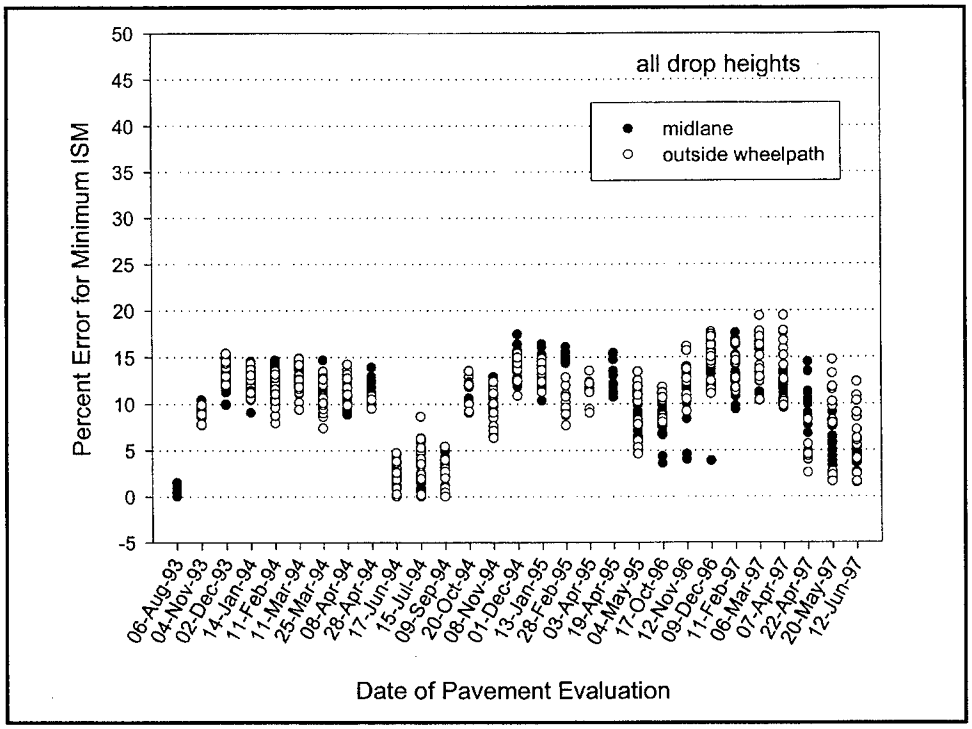
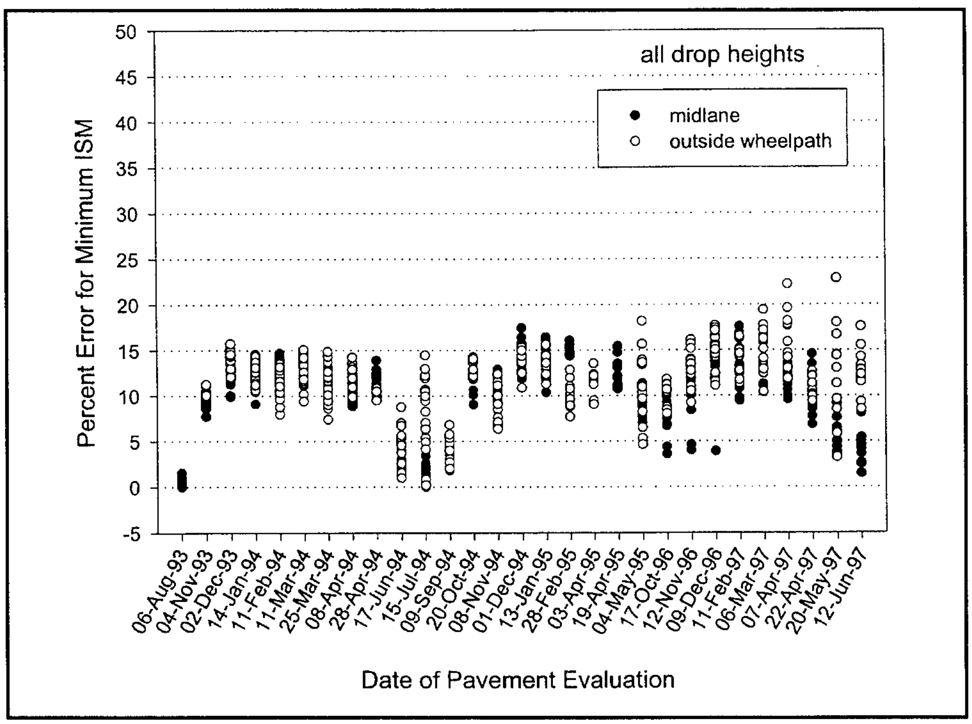


Figure E35. Errors in estimated minimum ISM caused by increasing station spacing to 15.2 m (50 ft) for test section 1001 in Utah



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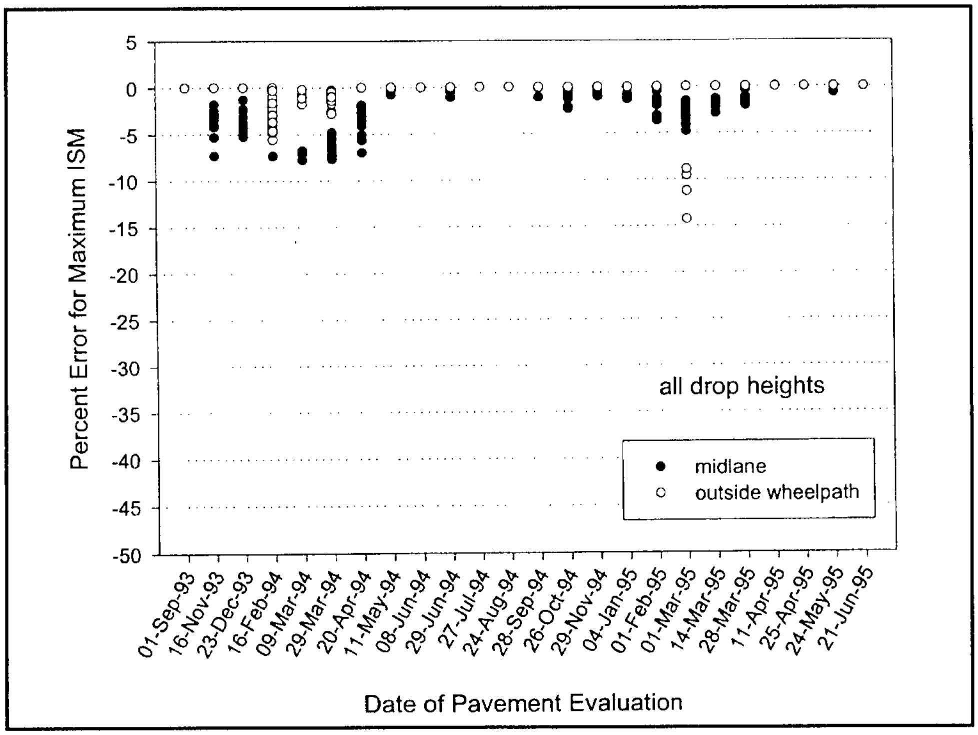

Figure E37. Errors in estimated maximum ISM caused by increasing station spacing to 15.2 m (50 ft) for test section 1002 in Massachusetts

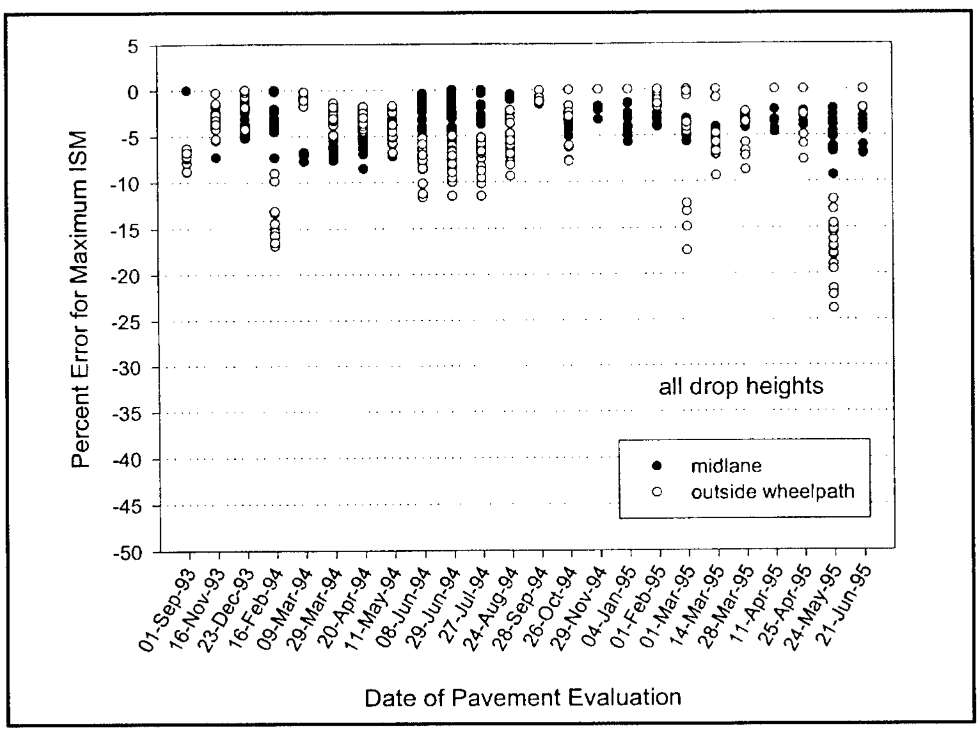

Figure E38. Errors in estimated maximum ISM caused by increasing station spacing to 30.5 m (100 ft) for test section 1002 in Massachusetts

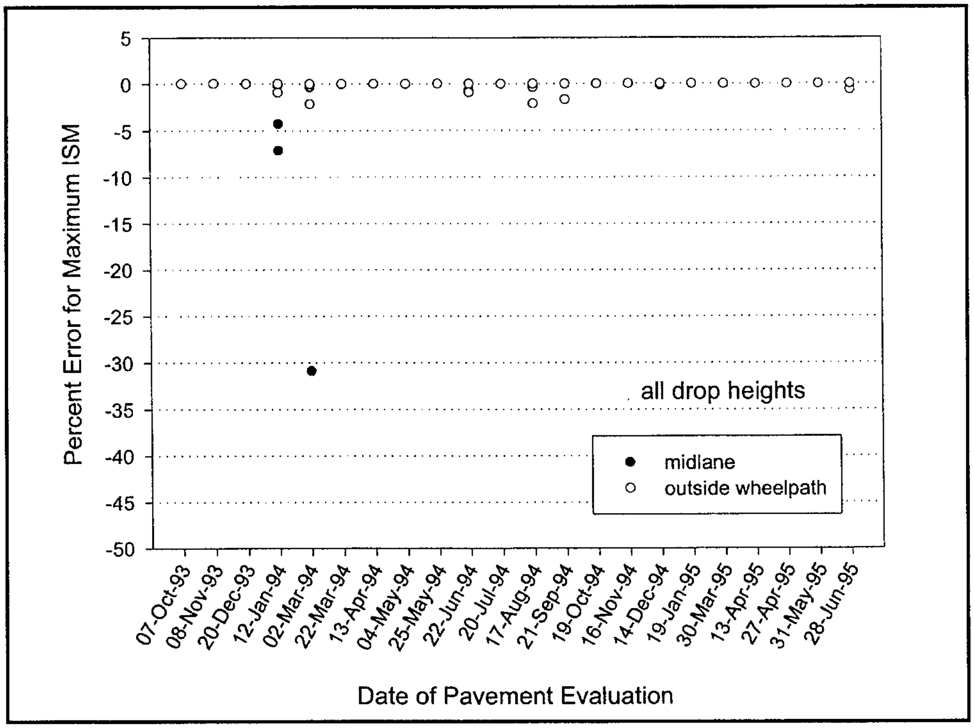

Figure E39. Errors in estimated maximum ISM caused by increasing station spacing to 15.2 m (50 ft) for test section 1002 in Vermont

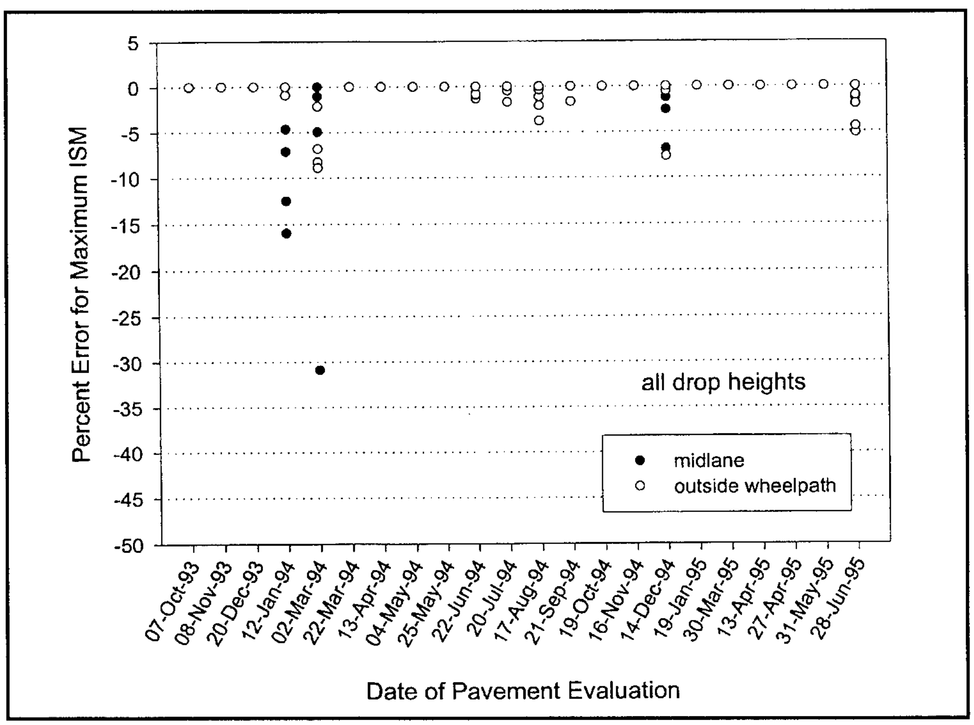

Figure E40. Errors in estimated maximum ISM caused by increasing station spacing to 30.5 m (100 ft) for test section 1002 in Vermont

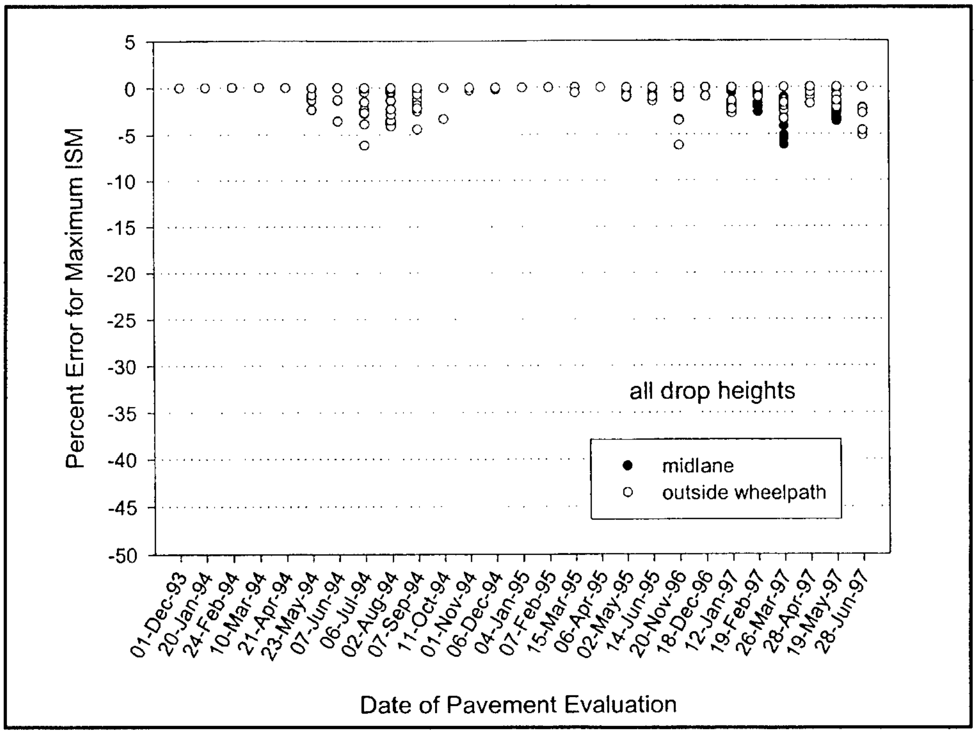

Figure E41. Errors in estimated maximum ISM caused by increasing station spacing to 15.2 m (50 ft) for test section 1060 in Texas

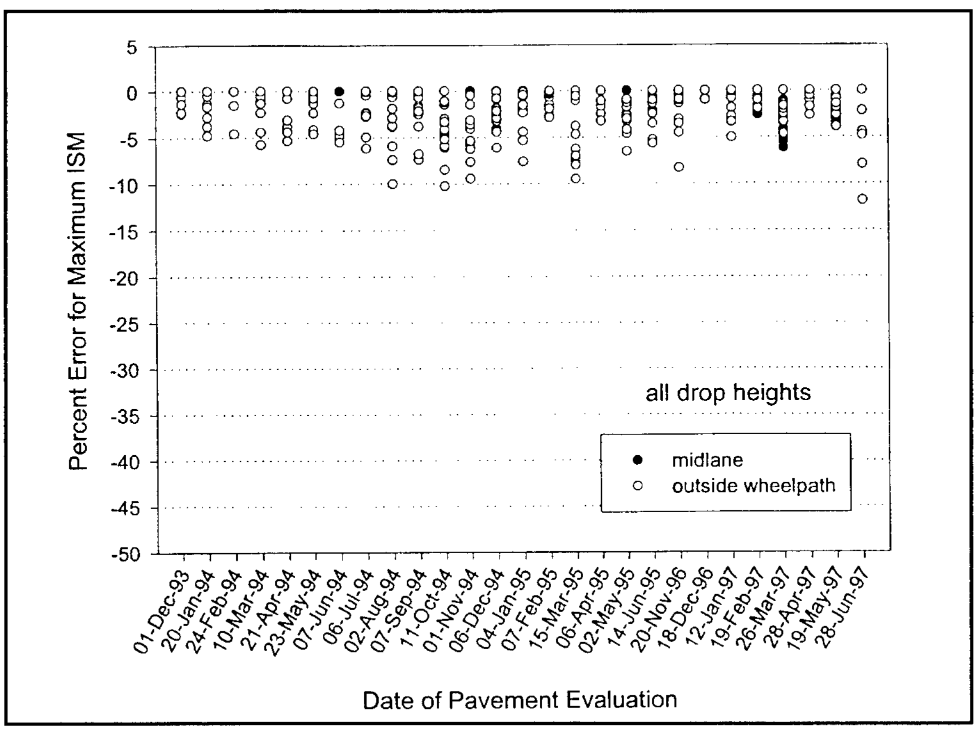

Figure E42. Errors in estimated maximum ISM caused by increasing station spacing to 30.5 m (100 ft) for test section 1060 in Texas

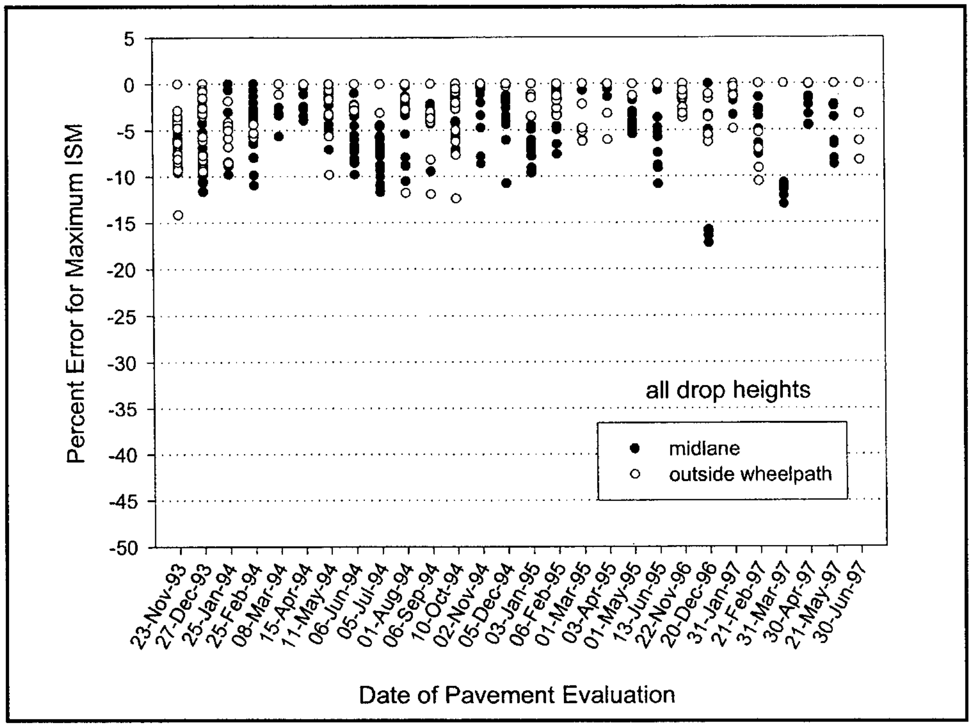

Figure E43. Errors in estimated maximum ISM caused by increasing station spacing to 15.2 m (50 ft) for test section 1122 in Texas

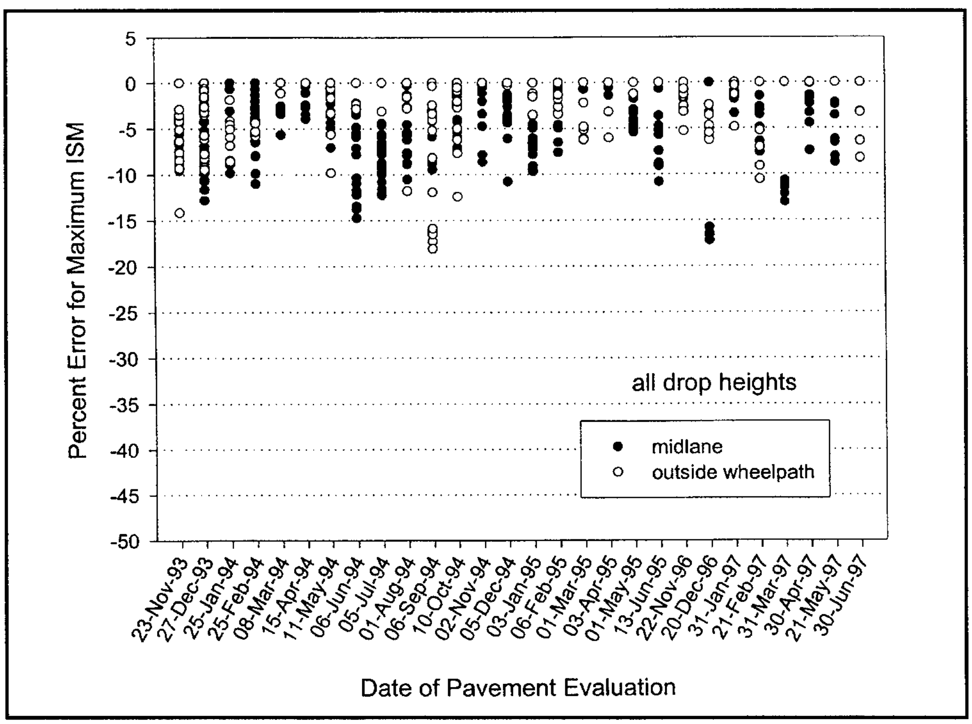

Figure E44. Errors in estimated maximum ISM caused by increasing station spacing to 30.5 m (100 ft) for test section 1122 in Texas

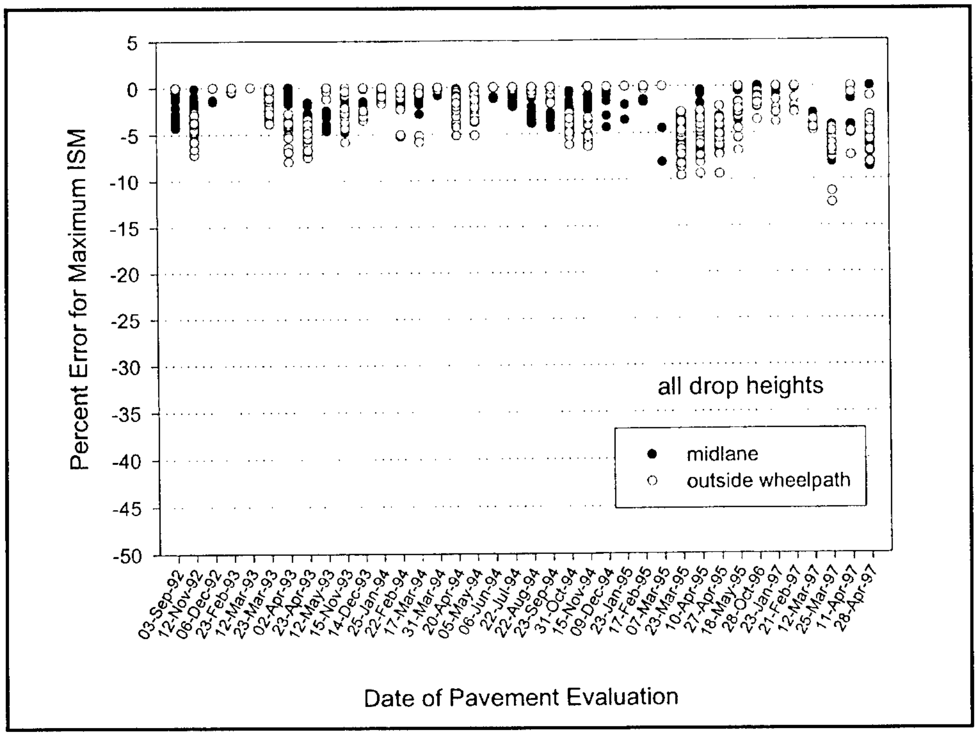

Figure E45. Errors in estimated maximum ISM caused by increasing station spacing to 15.2 m (50 ft) for test section 8129 in Montana

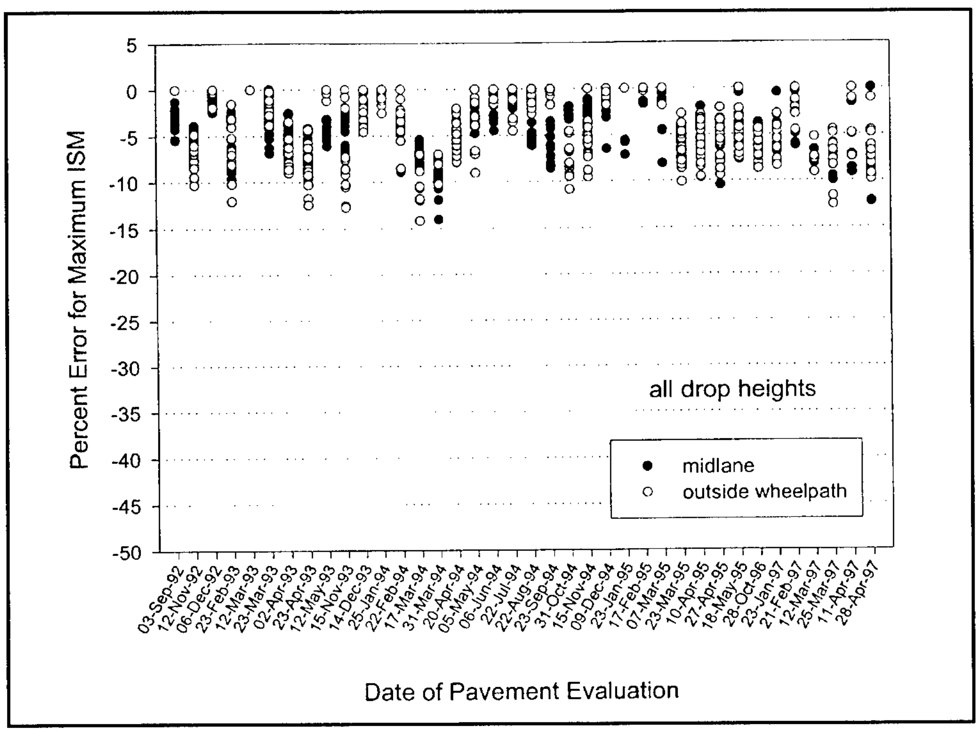

Figure E46. Errors in estimated maximum ISM caused by increasing station spacing to 30.5 m (100 ft) for test section 8129 in Montana

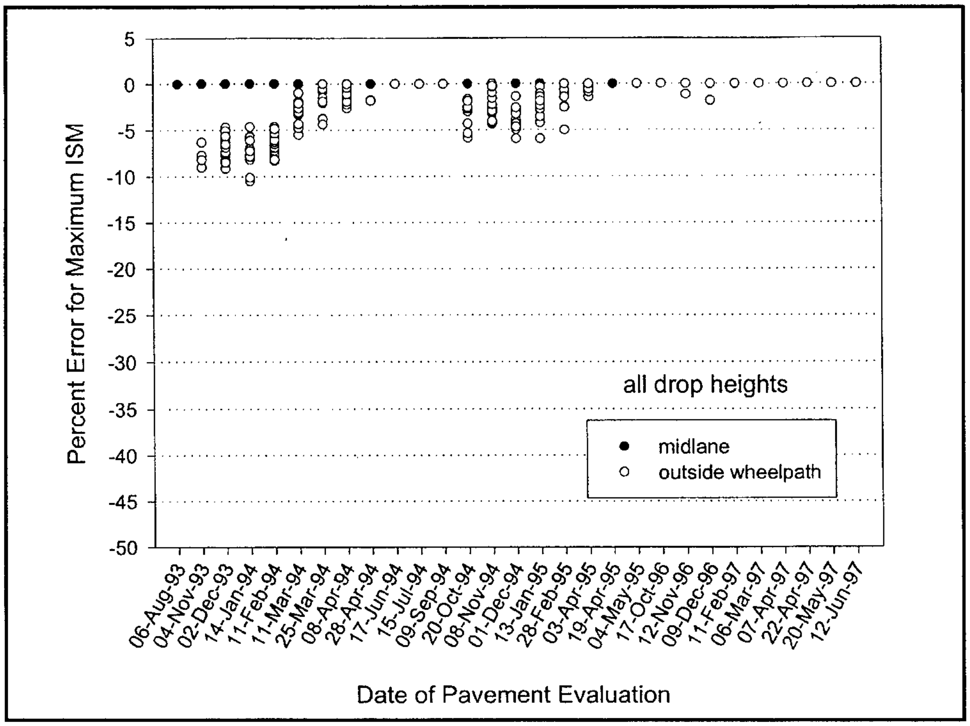

Figure E47. Errors in estimated maximum ISM caused by increasing station spacing to 15.2 m (50 ft) for test section 1001 in Utah

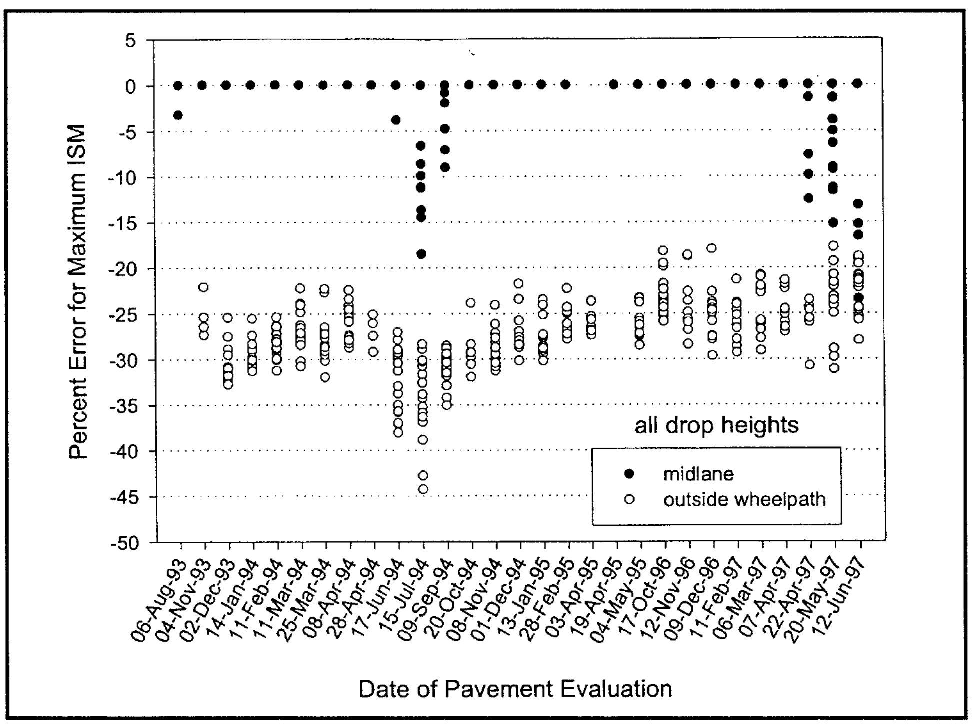

Figure E48. Errors in estimated maximum ISM caused by increasing station spacing to 30.5 m (100 ft) for test section 1001 in Utah

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14. ABSTRACT
The Strategic Highway Research Program, managed by the Federal Highway Administration, includes a pavement evaluation component as part of its Long-Term Pavement Performance study. These evaluations include the use of falling-weight deflectometer (FWD) test devices. The purpose of this project was to determine whether the FWD test procedures could be modified to reduce cost, without losing a significant amount of information. Procedural changes could include a decrease in the number of test replicates and/or an increase in the spacing between test stations. Variability between replicates was found to be relatively low; a reduction in replicate drops from four to two would not cause a substantial loss in information. An increase in spacing between tests from 7.6 m (25 ft) to 30.5 m (100 ft) would result in a substantial loss of information. An increase in spacing from 7.6 m (25 ft) to 15.2 m (50 ft) would be reasonable if test section responses to FWD were to be summarized as expected values and dispersions. If extremes in pavement response (e.g., minimum and/or maximum stiffness) were judged to be the most important results, the spacing between tests should not be increased from 7.6 m (25 ft).

15. SUBJECT TERMS
Falling-weight deflectometer
Non-destructive testing
Pavement performance
Spatial variability
Test variability

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
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