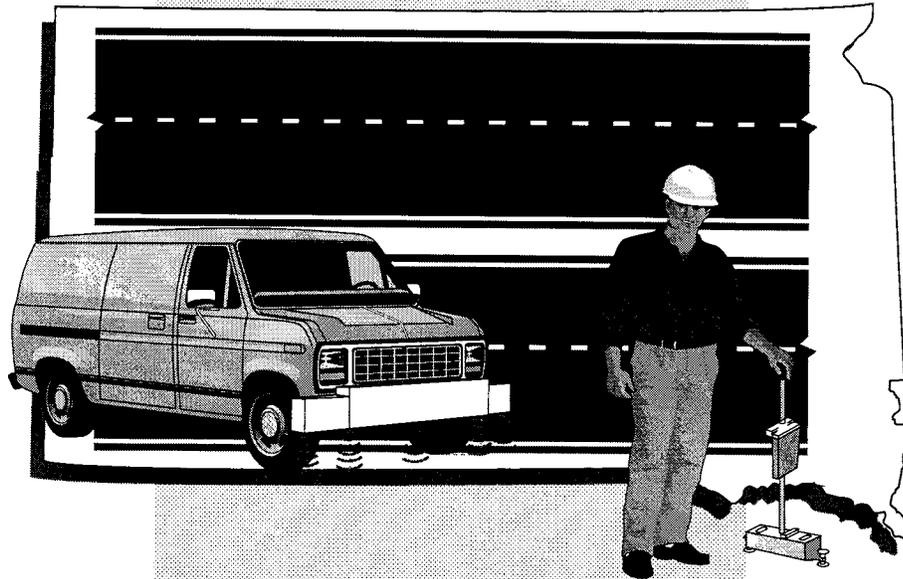FINAL REPORT

ASSESSMENT OF VIRGINIA'S HYBRID SOUTH DAKOTA ROAD PROFILING SYSTEM

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Abstract

        South Dakota Road Profiling (SDRP) systems have been widely sanctioned for use in assessing road roughness and rutting at highway speeds. Traditionally, these high-speed profiling systems have been built around ultrasonic height sensors. More recently, some designs have begun to substitute laser sensors to combat many of the limitations of sound-based equipment. The functional improvements possible with lasers are expensive, however. Whether the potential of lasers for high-speed profiling justifies the great increase in cost was a legitimate question.

        This report describes the steps that the Virginia Department of Transportation took to address that issue. In general, this research has found that both sensor types are capable of performing very well and with reasonable agreement. Repeatability tests indicated that the roughness indices calculated from laser-based profiles are less subject to run-to-run variability than those developed from ultrasonic profiles. Tests to evaluate the effects of vehicle speed and sampling rate on the estimate of roughness have returned less conclusive results. Both tests suggested that the ultrasonic-based data was more highly correlated with the control data (i.e., that based on data collected with the Face Companies' Dipstick[R]) than the laser-based. The laser data, however, could be shown to be slightly more accurate, on average, than that based on the ultrasonic.

        Unfortunately, although the performance of the ultrasonic sensors on conventional surfaces has been adequate, their reliability has become a serious concern. In Virginia, humid surveying conditions are often unavoidable and the problem of wet ultrasonics has become more than a simple inconvenience. Hardware reliability may be the most compelling reason to migrate to pure laser roughness measurement. The adoption of only laser-based equipment in future purchases or leases is recommended.

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(The opinions, findings, and conclusions expressed in this
report are those of the authors and not necessarily those of
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ABSTRACT

South Dakota Road Profiling (SDRP) systems have been widely sanctioned for use in assessing road roughness and rutting at highway speeds. Traditionally, these high-speed profiling systems have been built around ultrasonic height sensors. More recently, some designs have begun to substitute laser sensors to combat many of the limitations of sound-based equipment. The functional improvements possible with lasers are expensive, however. Whether the potential of lasers for high-speed profiling justifies the great increase in cost is a legitimate question.

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INTRODUCTION

Road and bridge roughness has been actively studied at the Research Council since the mid 1960s.[1-4] For most of that time, the instruments used to assess rideability have been response-type road roughness measurement (RTRRM) systems. As the name implies, RTRRMs estimate rideability based on the response of the instrumented vehicle (or trailer) traveling at a specified speed over a pavement's surface. Unfortunately, the nature of these systems make their results extremely instrument-specific and subject to wide variability. Any change that affects the response of the vehicle to the surface (suspension or tire wear, vehicle and operator weight changes, etc.) will affect the estimate of roughness.

To counter the shortcomings of RTRRMs, more contemporary road roughness equipment and strategies have attempted to mitigate the bias imposed by ride meter suspensions by basing roughness estimates on the actual road surface profile. The last formal road roughness project conducted at the Research Council evaluated a profile-based system.[4] The K.J. Law Model 8300 Roughness Surveyor evaluated in that study collects the profile of a single wheelpath using, among other instruments, a bumper-mounted ultrasonic height sensor. The study objectives were to assess its suitability for collecting inventory data, performing construction quality control and acceptance testing, and performing research-oriented surveys. This study, which began in 1985 and was completed in November 1992, was plagued by equipment failures and manufacturer delays. Ultimately, the study found that although the Model 8300 Surveyor was a useful roughness testing device, it had serious limitations. Most significant of which were the strong influences of testing speed and temperature on roughness test results.

Since the development of the first high-speed profiler, many improvements have been made in the ability to collect and process road roughness information. In the late 1980s, in order to collect the Federally required roughness for Virginia's approximately 3000 Highway Performance Monitoring System (HPMS) sites,[5] Virginia purchased a South Dakota style road profiler. This system, based on the research led by Mr. David Huft of the South Dakota Department of Transportation,[6,7] simultaneously collects three

profiles (one for each wheelpath and one for the lane center). From these profiles, software calculates a measure of roughness and an estimate of rutting at specified intervals along the roadway.

The South Dakota Road Profiler (SDRP) and the K. J. Law Model 8300 both fall into a category of instruments called accelerometer established inertial road profiling (AEIRP) systems. Three fundamental components are necessary to enable an AEIRP to collect profiles. The first is the accelerometer(s) with which a positional reference plane(s) for the vehicle is maintained. The second is an electronic distance transducer, which provides a record of horizontal distance traveled. The third is the height sensor which measures the distance of the pavement surface below the reference plane established by the accelerometer. The synchronized calculation of the difference between the vehicle displacement and height measurements allows the system to compute the highway profile.

Because it is the height sensor that actually interfaces with the highway surface, in some respects it is the most critical element in the system. Many of the first height sensors used on inertial road profiling systems were ultrasonic and operated on much the same principle as the first auto-focus cameras. More recently, fabricators have begun to substitute laser sensors to combat the inherent limitations of sound-based equipment. The most significant of these limitations is the effect of temperature, wind, and moisture on the propogation of sound. The speed of the collection vehicle and the amount of macrotexture present in a surface have also been shown to influence the performance of ultrasonics.

The functional improvements possible with lasers are expensive. Whether the potential of lasers for high-speed road profiling and rut-depth measurement justifies the great increase in cost is a legitimate question. Compatibility and consistency with older ultrasonic systems also concern highway agencies trying to exploit new technologies without sacrificing their in-place investments. As ride quality specifications incorporating these devices receive more serious consideration, officials are becoming more preoccupied with the detail accuracy and repeatability of these instruments.

PURPOSE AND SCOPE

In early 1994, to address these concerns and investigate the potential of laser-based profiling, the Virginia Department of Transportation acquired a laser-enhanced SDRP. This hybrid system is equipped with three *ultrasonic height* sensors, one *ultrasonic correction* sensor, and two *laser height* sensors. It is capable of collecting road profile data (left and right wheel paths) with both ultrasonic and laser instruments, simultaneously. With this system, a unique opportunity existed for making a conclusive comparison of the capabilities and limitations of both sensor types. Correlation analyses

did not have to contend with the errors that result when independent vehicle systems track different paths, start and stop at different locations, and often have different operators.

The objective of this study was to critically evaluate laser and ultrasonic sensors for use as the height sensing components on Virginia's SDRP vehicles. Investigation of the following five issues constituted the largest portion of this comparison analysis:

1. Laser and ultrasonic profile accuracy (ideal profiling conditions).
2. Laser and ultrasonic profile repeatability (ideal profiling conditions).
3. Evaluation of the effects of varied sampling and averaging rates on computed indices.
4. Evaluation of the effects of varied operating speeds on computed indices.
5. Surface texture influence on equipment alternatives.

Surfaces tested during the instrument repeatability tests included standard medium textured hot mix asphalt concrete (HMAC), a latex emulsion asphalt slurry seal, machine-tined and burlap-dragged portland cement concrete (PCC), a gap-graded stone matrix asphalt concrete (SMA), and a chip seal. Surfaces specifically targeted for sampling rate and vehicle speed tests also included the medium textured HMAC, the slurry seal, the machine-tined PCC, and the SMA surface, as well as two composite sections (medium textured asphalt overlay over jointed PCC) and a flushed and rutted smooth HMAC. All of these surfaces are common in Virginia.

Unfortunately, an all-inclusive comparative analysis of sensor types has not been possible. The most important issue that has not been formally addressed is the relative sensitivity of sensor types to temperature extremes. Circumstances that have prevented or hampered testing include vehicle breakdown, instrument malfunction, and other obligations of the vehicle operators and the research staff.

METHODS

Within the scope of work just described, two data sets were developed. The first was primarily intended to support the instrument repeatability tests. The second, somewhat overlapping the first, was established to allow an assessment of the effects of varied sampling rates and vehicle speeds. Sensor accuracy and the influence of surface texture could also be addressed from within these data.

The roughness of each test performed is recorded in terms of the International Roughness Index (IRI). The IRI, which is the most standardized method of reporting roughness, is produced through a reference quarter car simulation (RQCS).[8] This simulation is applied to a measured longitudinal profile and can be calculated for nearly

any interval. Strictly speaking, IRIs are specific to an individual profile (and normally correspond to an individual wheelpath). For much of this project, however, roughness is reported and compared by lane average. This lane average is the mean of the values reported for the left and right wheelpaths of a single test. Lane averages were used to help consolidate the data, and because lane values are most consistent with current and proposed reporting procedures within the state.

Repeatability

Testing Procedures

The procedures used to test repeatability were identical to those used in the assessment of the KJ Law 8300.[4] Like the earlier study, a test of one surface involved 30 consecutive replicates of the same pavement section. Because data from sites used to conduct more rigorous field testing (with texture tests, baseline profiling, etc.) were being lumped with those which could be conducted under traffic, all repeatability analyses were confined to selected lengths of 173 meters (0.1 mile).

Data Analysis

Separate reports were developed for each run and consolidated using the maker's software. These reports were parsed into spreadsheets that contained just the selected 173 meter (0.1 mile) section for each of the 30 back-to-back runs. From these worksheets, a separate series of statistics was generated for each surface, sensor type, and wheelpath. Specifically, those statistics included the mean, the standard deviation, the coefficient of variation, the maximum, the minimum, and the IRI range for the 30 replicates. Also calculated for each surface and instrument type were the *coefficients of variation, v* (*v* is taken as the standard deviation as a percentage of the mean). Perhaps the most encompassing statistic was the N(req'd) value which estimates the *number of samples required* to find the real roughness, given specified error tolerances and confidence levels. The equation used to calculate N(req'd) is

$$N_{reqd} = \left[\frac{(t)(v)}{E}\right]^2$$

where *t* is a probability factor (2 for 95 percent confidence level and 30 samples), *v* is the coefficient of variation, and E is the tolerance (5% in this case). The reader is again referred to K.H. McGhee[4] for a table of probability factors corresponding to the degrees of freedom and desired confidence levels.

4

Seasonal Repeatability

The initial repeatability assessment was conducted in the spring of 1995. Following most of the overlay season of the summer of 1995, the repeatability sites established in the spring were visited again in late fall. There were two objectives in doing so. The first was simply to examine what influence, if any, the temperature differences had on the ability of the respective height sensing devices to provide repeatable results. The second, assuming that reliable information would still be possible under fall conditions, was to observe any legitimate change in ride that may occur over a two-season timespan (spring/summer, summer/fall).

Just as in the 30-run repeatability assessments conducted with the single-season data from April and May, the November and December tests included multiple runs over the same test site. In the interests of time, the fall tests were terminated after 10 iterations per site. Otherwise, the same statistics generated for the spring repeatability assessment were produced for each site. Of course, the probability factor used to calculate the number of samples required to determine real roughness was adjusted for the reduced degrees of freedom (instead of 2, t was taken as 2.23).

Rate and Speed Tests

Site Selection and Preparation

With minor modification, the convention applied to selection and preparation of the rate and speed sites was borrowed from the Road Profiler User's Group study from 1993.[9] Each site was a measured 173 meter (0.1 mile) section of homogeneous surface, selected to avoid any exaggerated horizontal or vertical curvature and also any interference by adjoining roads and driveways. The primary difference from the RPUG sites was that these sites were located using a lead-in section of an even multiple of site length (2 or 3 x 173 m, or 0.2 to 0.3 mile). The need for artificial bumps to precisely locate sections was eliminated by iniating each run from a complete stop at the beginning of this lead-in.

Once a 173 meter (0.1 mile) section was selected and the beginning established, the wheelpaths were located. The exact position of the wheelpaths relative to the center line and the edge of pavement varied depending on the width of the lane. Lane widths varied from approximately 3.3 to 4 meters (10 to 12 feet). Regardless of the width of the lane, all site wheelpaths were located 1.75 meters (69 inches) apart to correspond with the known spacing of the wheelpath sensors. With two people using a measuring tape and an operator closely monitoring the vehicle distance measuring instrument (DMI), the center of each wheelpath was marked with keel at 8.2 meter (25 foot) intervals. With these intervals established, a crew of three people placed chalk lines longitudinally for the

extent of each 173 meter (0.1 mile) test section. Chalk lines were also snapped transversely at the marked 8.2 meter (25 foot) intervals.
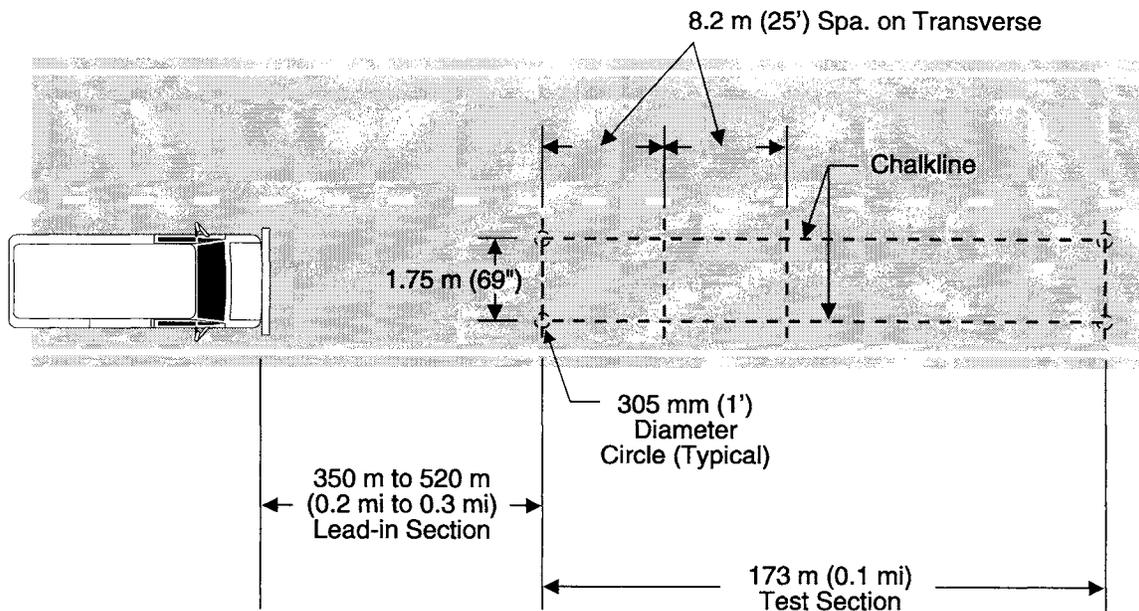
Figure 1. Test Site Layout

Testing Procedures

With site layout complete, a Dipstick[R] instrument (manufactured by The Face Companies) was used to collect control profiles. A "boxing" technique was used to supplement the accuracy of these profiles. This technique consisted of a continuous survey down one wheelpath, across the lane at the site end, a return walk down the opposite wheelpath, and then closing the box back to the starting point as shown in Figure 1. Test Site Layout.

While the Dipstick[R] operator performed his survey, two other technicians conducted sand patch tests. These tests, which were conducted in accordance with ASTM Standard E 965 - 87, provided a simple, objective measure of surface macrotexture. These values were later used to investigate the influence of surface texture on equipment alternatives.

Lastly, transverse profiles were collected with the Dipstick[R] at the marked 8.2 meter (25 foot) intervals, for a quick estimate of full transverse rutting for each site.

6

When control data collection was completed, the site was cleared and testing with the hybrid SDRP began. A complete test of a selected site included four repeat runs at 32 km/h (20 mph), one run at 48 km/h (30 mph), one at 64 km/h (40 mph), and at least three at 80 km/h (50 mph). Table 1 lists the run sequencing, complete with sampling rates and vehicle speeds. The varying of rate is only possible at 32 km/h (20 mph) due to characteristics of the ultrasonics which prevent higher resolution sampling at higher speeds. As the table shows, once the run at 32 km/h (20 mph) and a sampling rate of 6 for both instruments was complete, the sampling rate scheme was set to 6 and 3 for the ultrasonics and lasers respectively, and maintained for the remainder of the tests. These sampling settings were used because they represent the normal mode of operation for road roughness testing (the lasers are routinely operated at twice the sampling resolution of the ultrasonics).

Table 1. Rate and Speed Test Sequence

Run Number	Ultrasonic Sampling Rate	Laser Sampling Rate	Vehicle Speed
1	2(120mm/sample)	2(120mm/sample)	32km/h(20 mph)
2	4(240mm/sample)	4(240mm/sample)	32km/h(20mph)
3	6(360mm/sample)	6(360mm/sample)	32km/h(20 mph)
4	6	3(180mm/sample)	32km/h(20 mph)
5	6	3	48km/h(30 mph)
6	6	3	64km/h(40 mph)
7	6	3	80km/h(50 mph)
8	6	3	80km/h(50 mph)
9	6	3	80km/h(50 mph)

Data Analysis

To ensure complete flexibility in future analyses, the data from every test were stored in their rawest state. In binary (machine language), the complete data sets are large. Completely converted to ASCII, the database size would have been intractable. To conserve storage space and minimize confusion, reports of the results only extracted the information relevant to the current analysis.

As such, reports for each run of each site for each sensor type were generated and summarized using software provided by the vehicle fabricator (International Cybernetics Corporation). Typically, only a single line (out of 10 to 15) of each roughness report was necessary. Fortunately, a summarizing routine provided by the manufacturer was helpful for gleaning that data record. Once these records were lumped into a single text file, the file was drawn temporarily into Microsoft Excel. Appropriately parsed, the resulting spreadsheets were imported into a Microsoft Access database. The entire database was composed of three tables. The first included a record for each run and described the

sensor type, the vehicle speed, and sampling rate used for the test. The second table also stored a record per run, but included only the measured results for roughness and rutting. The last table provided specific location information, site type (i.e., rate & speed and/or repeatability), operator identity and testing date, and measured texture data and any distress information. With the database manager, unchanging information about a given site, such as location, type, and texture, could be recorded once, stored independently, and combined as necessary.

Once the database was functional, analysis could begin. First, the roughness data was queried to glean only those records containing information of a certain type (for example, sensor = laser, collection rate = 2, speed = 32 km/h or 20mph). Combining individual queries, new spreadsheets were built to investigate the various relationships hypothesized to exist within the data. Of obvious interest was the performance of the respective height-sensing devices, compared to each other and against the Dipstick[R]. One series of spreadsheets was developed to statistically relate the three 32 km/h (20 mph) runs at each site for each instrument and sampling rate. A second series of spreadsheets lumped the data associated with the tests conducted at normal sampling rates and increasing speeds. Contributing to the graphical and numerical assessments of each set of results were scatter plots with linear trend lines, correlation analyses of one instrument versus another, bar plots of the differences observed by each instrument at changing rates and speeds, and a correlation analysis of instrument difference and speed.

FINDINGS

Profiles

The initial inclination, given the power and sophistication of modern hardware and software, was to devise a method for statistically reducing the raw profiles generated by the competing devices and basing any comparisons on their respective performances at that level. The following figures were developed to observe the products of the alternative profiling devices in their most fundamental states. The figures are representative profiles assembled from a single wheelpath of a single test site. Figure 2 illustrates the profile as collected statically with the Dipstick[R]. One line represents the unaltered road surface profile, complete with its design slope. The other line has been rotated to remove any slope imposed by design. This rotated profile was produced to provide a more equitable comparison with the SDRP, a system that does not return profiles with absolute elevation information.

Figure 3 depicts the profile, as registered by the laser and ultrasonic equipment on the SDRP. Figure 4 is a zoomed portion of the same profile that shows that the two devices are indeed perceiving features slightly differently. The next illustration (Figure 5) demonstrates that although the similarities between the two SDRP instruments are

remarkable, the profiles they provide appear quite different from that determined statically. Curiously, in spite of this dramatic dissimilarity, the IRI calculated using the laser-based profile of this particular test site was within 3 percent of that calculated using the profile collected with the Dipstick[R]. The roughness, as estimated using the ultrasonic-based profile of this test site, differed from the Dipstick[R] by less than 14 percent.
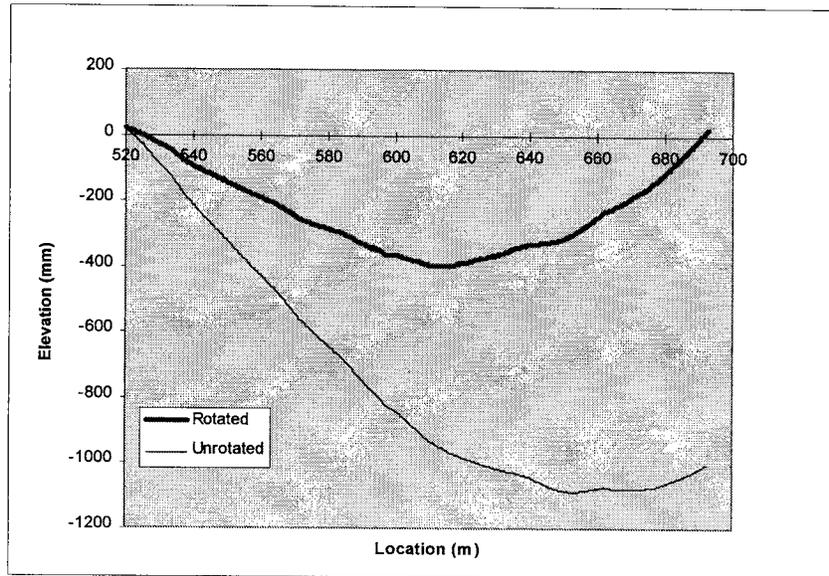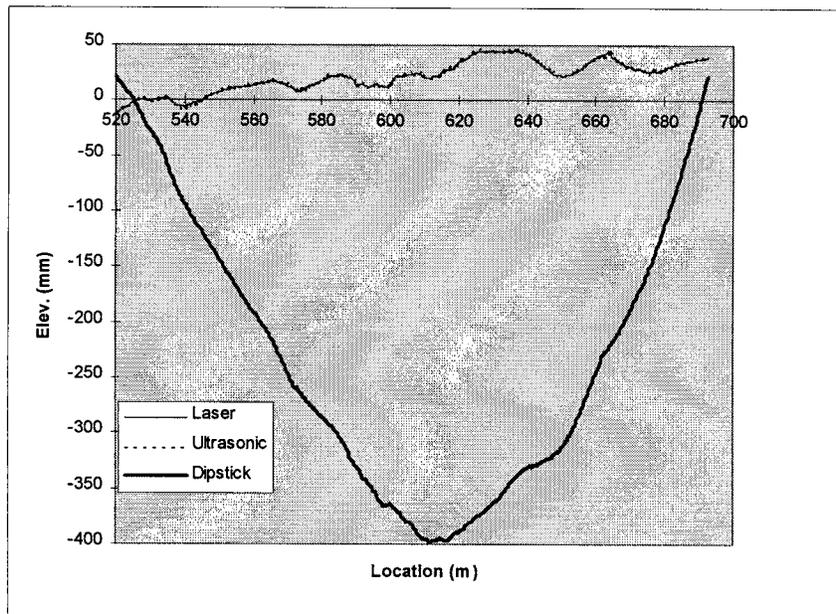

Figure 2. Dipstick Profiles
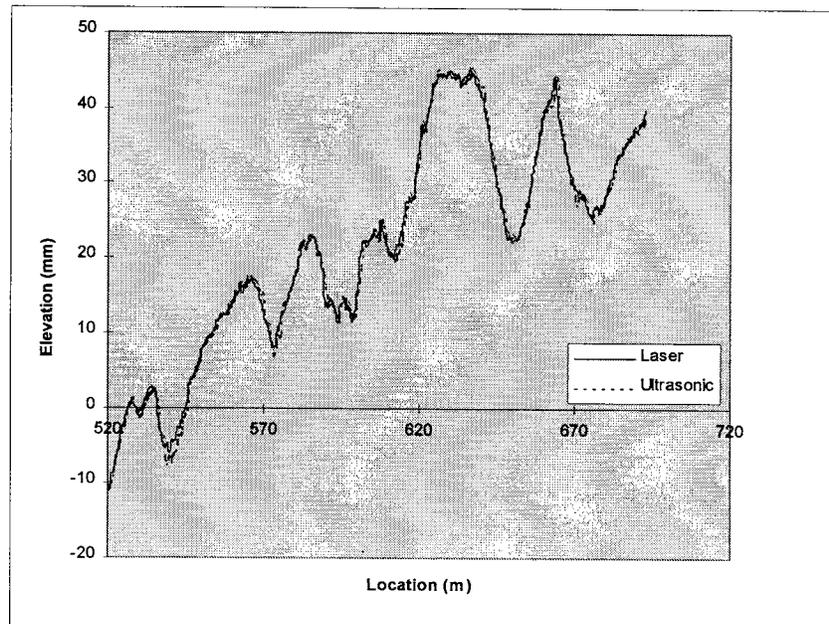
Figure 3. Laser and Ultrasonic SDRP Profiles

9
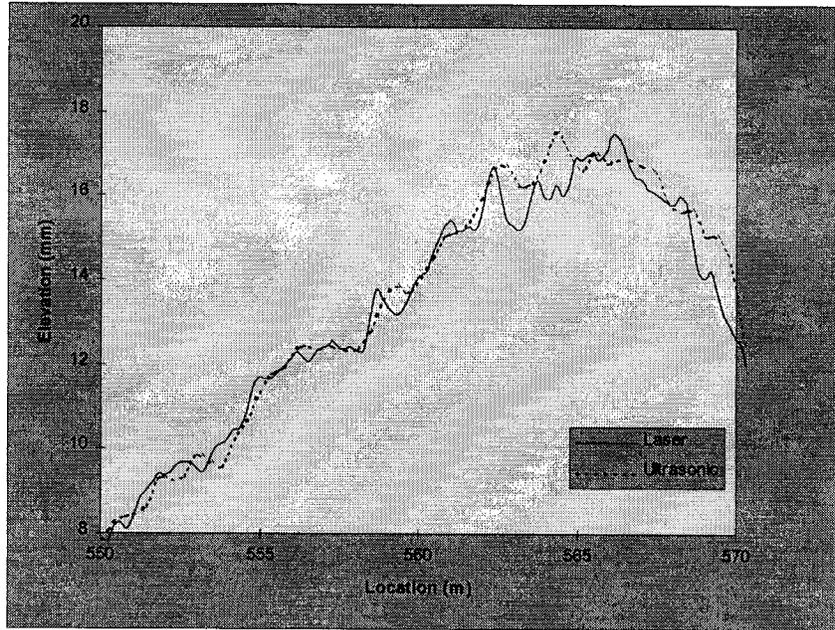
Figure 4. Laser and Ultrasonic SDRP Profiles (Magnified)

Figure 5. All Device Profiles

Unfortunately, the database that would have resulted had the analysis attempted to compare devices profile by profile would have been prohibitively large. In fact, even after deciding to evaluate the instruments based on a section's calculated IRI, the further consolidation to lane averages, as opposed to individual wheelpaths, was made for this discussion.

Repeatability

Table 2 summarizes the results of the single-season repeatability analyses. These very general statistics suggest that under the prevailing test conditions, both instrument types (ultrasonic and laser) can provide very respectable results. A simple statistic that can be fairly informative is the *range* over which the measured indices vary over 30 runs. Here, an absolute value for range was included, as well as the value of range as a percent of the mean IRI. Generally speaking, the smaller the *ranging* characteristic of an instrument, the more confidence that can be associated with it. Note that these results indicated that a laser-based index can be expected to drift approximately 3% less than indices originating from ultrasonics.

Also included in the table are the average *coefficients of variation, v,* listed by instrument type. This statistic normalizes the variability of the equipment by reporting the standard deviation of a series of tests as a percentage of the mean. It provides a very concise estimate of expected repeatability from one replicate to the next.

The last statistic is the *number of samples required,* $N_{req'd}$, to find the real roughness, given the tolerances and confidence discussed earlier. This statistic combines the variability as reported by the coefficient of variation with ideas of normal distribution from conventional materials testing theory. These tests indicate that, on average, one more sample will be necessary when collecting ultrasonic roughness than is required with lasers. For a single site's assessment, the savings from one repetition may not appear critical. However, extrapolated to the administration of rideability specifications, a reduction in one run per site for every site in a season's overlay schedule would quickly become significant.

Table 2. Summary of Repeatability Tests

|	Two-Wheelpath Average	
	30 REPLICATES EACH SITE	
STATISTIC	Ultrasonic All Surface Average	Laser All Surface Average
AVG IRI(mm/m)	1.80 (114 in/mi)	1.67 (106 in/mi)
Max IRI(mm/m)	1.91 (121 in/mi)	1.75 (111 in/mi)
Min IRI(mm/m)	1.69 (107 in/mi)	1.58 (100 in/mi)
Range(mm/m)	0.22 (14 in/mi)	0.17 (11 in/mi)
Range (% AVG IRI)	12.9	9.9
Std Dev.	.05	.04
v(%)	3.1	2.3
N(req'd)	1.7	0.9

11

Figure 6, Figure 7, and Figure 8 depict the statistics discussed above as they were generated by individual site. Radar-type plots have been used to emphasize the relative performance of each instrument. As discussed previously, a smaller value indicates better repeatability. For this type of plot, a tighter dispersion of a statistic suggests less variability. As expected, the ultrasonic-based equipment had the most difficulty with the more exotic surfaces. The rather pronounced "star" points on these images clearly illustrate the relative difficulty the ultrasonic equipment had in handling the stone-matrix asphalt (SMA) and the machine-tined concrete (JPCP) surfaces.
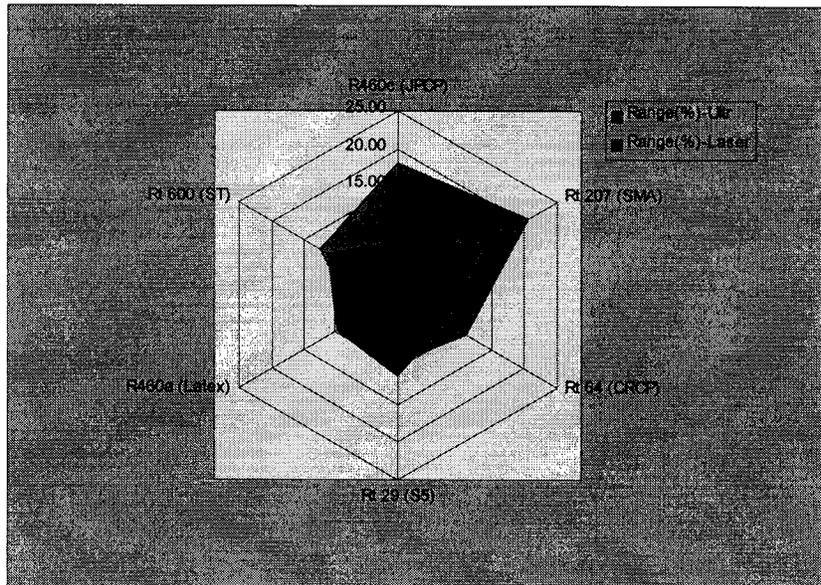
Figure 6. 30-Run Repeatability by Range
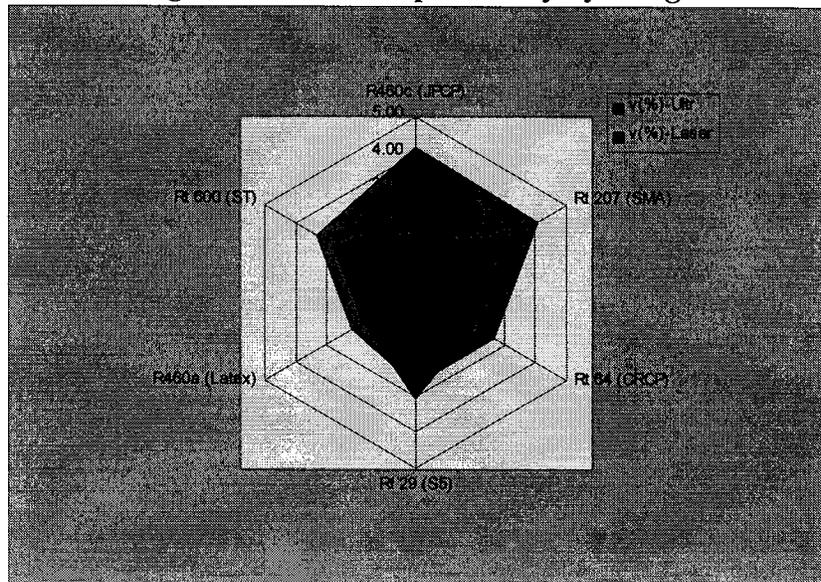
Figure 7. Coefficients of Variation
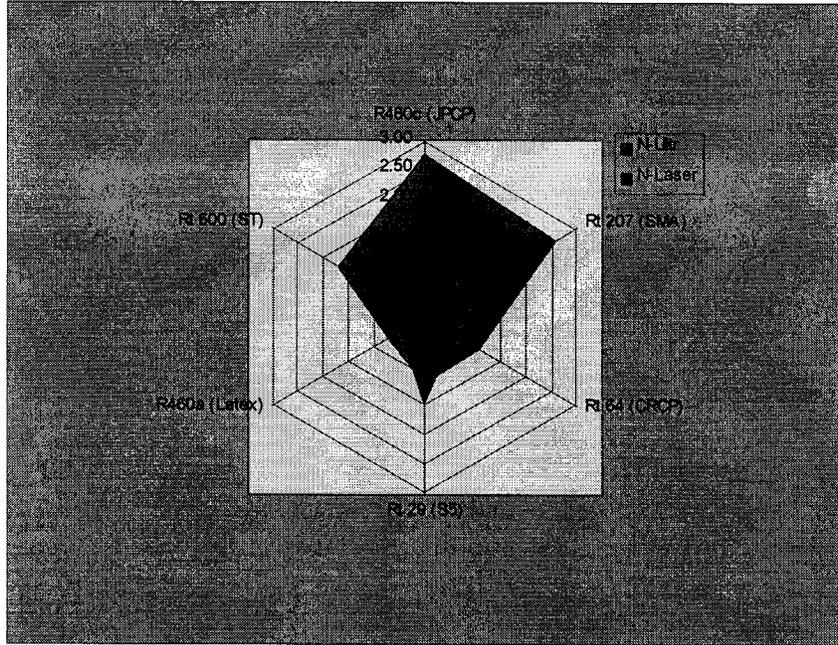
Figure 8. Estimated Number of Samples Required

Seasonal Repeatability

The next several figures present the findings of a late-project look at seasonal repeatability. For general comparative purposes , Figure 9 is a line plot of the average roughness of each site, estimated using both SDRP device types in both seasons. As expected, there appears to be very little change in the ride quality of the CRCP pavement on Interstate 64. In fact, the values reported by both device types, in both seasons, are remarkably similar. The same is essentially true for the deteriorated HMAC (S5) pavement on Route 29 in Albemarle. On the other hand, the surface treated (ST) pavement appears to have grown slightly smoother since the previous Spring.

The next three images are the radar plots discussed earlier with the results of the Fall repeatability tests added. The tendency of the ultrasonics to range significantly when testing the semi-exotic surfaces (SMA and tined concrete) is not as prevalent in the fall tests. This may be due, in part, to the reduction in number of tests performed. That is, the 20 fewer tests conducted in the fall were 20 fewer opportunities for exceptionally high or low measurements.

Nonetheless, there was moderate deterioration in repeatability exhibited by the ultrasonics in the fall tests. This deterioration is emphasized by the coefficient of variation and the calculated number of samples required. In each, the series portraying the fall ultrasonic values tend to envelop the other three data series.
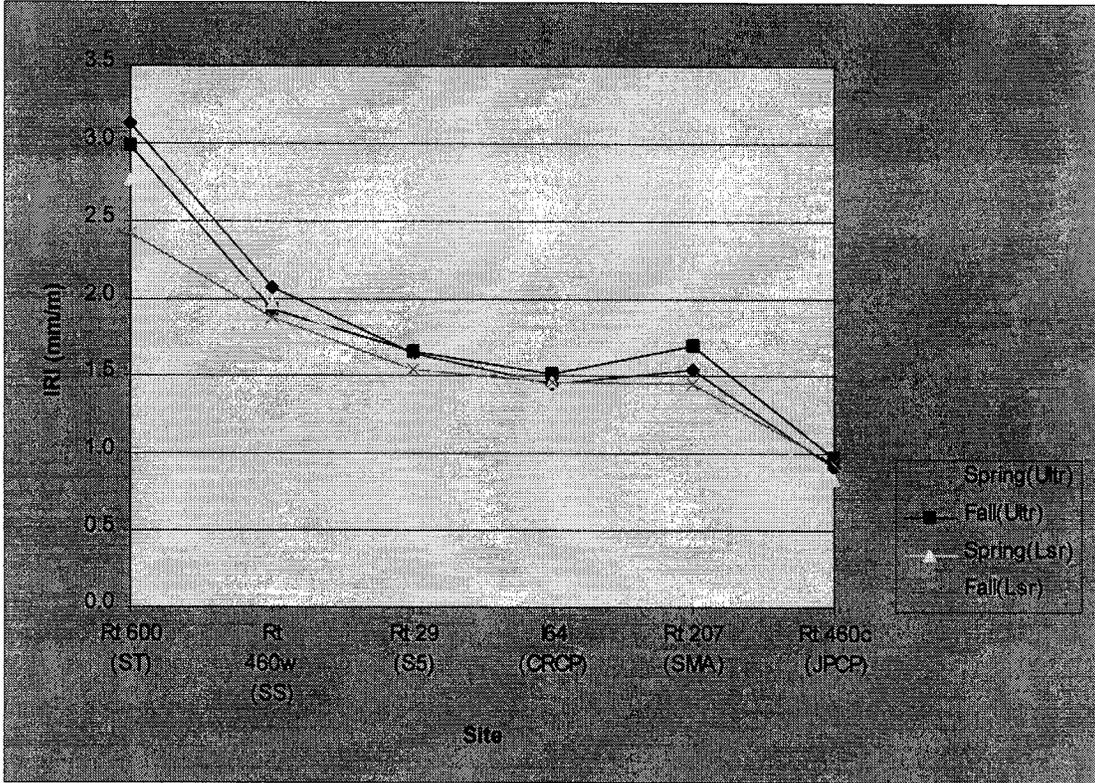
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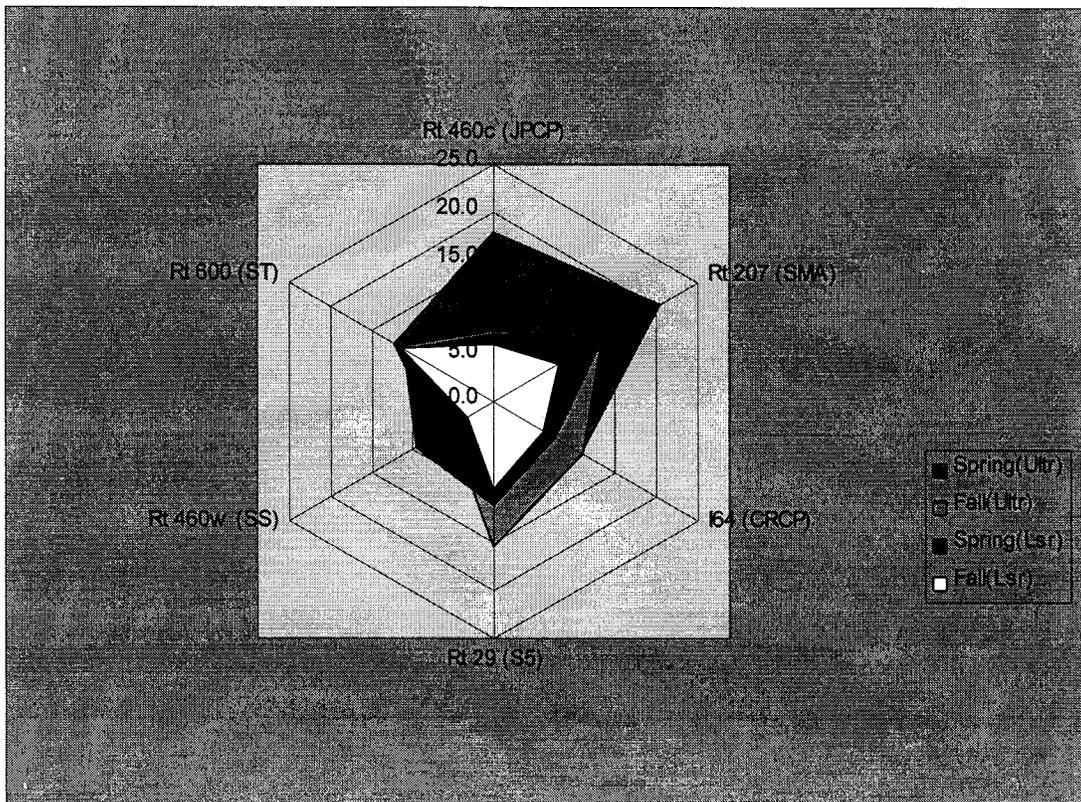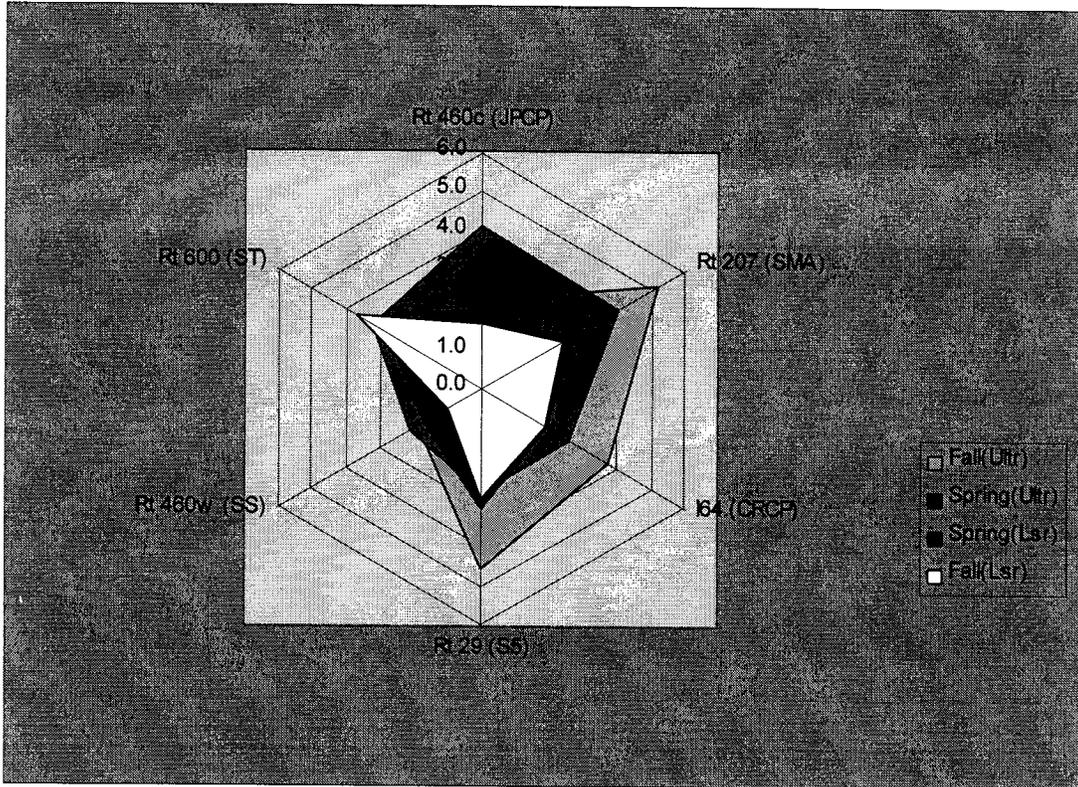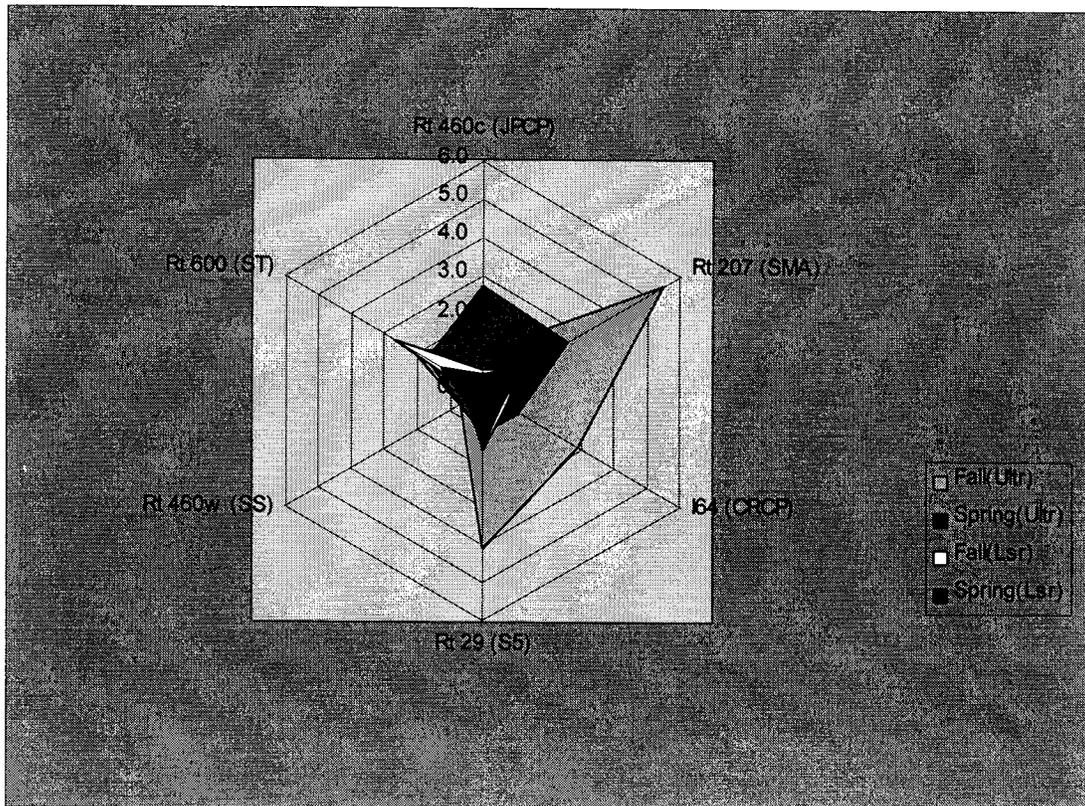**Figure 9. Average Site Roughness**

Figure 10. Ranging Percentage

14

Figure 11. Coefficient of Variation

Figure 12. Number of Samples Required

Rate and Speed

Table 3 lists the surface types and measured macrotextures for the evaluated rate and speed sites.

Table 3. Surface Types and Macrotextures

Site ID	Surface Type	Macrotexture
R15S2	S5(flushed)	0.326mm (0.01283 in)
R15S1	S5	0.388 mm (0.01528 in)
R460C	JPCP	0.501 mm (0.01974 in)
R460W	Latex Seal	0.599 mm (0.02359 in)
Rt29S1	S5(alligator)	0.634 mm (0.02496 in)
R13S2	S5(compos.)	0.847 mm (0.03333 in)
R13S1	S5(compos.)	0.893 mm (0.03515 in)
Rt207	SMA	1.331 mm (0.05239 in)

The effects of sampling rate and collection speed were tested through two independent comparisons with the "baseline" Dipstick[R] information. As expected, data from all sampling rates and testing speeds were highly correlated with the results of the Dipstick[R]. Curiously, the lasers were not the best performers in either evaluation.

Rate

Figure 13 and Figure 14 are scatter plots comparing roughness indices generated from data collected by the competing SDRP instruments and data based on the Dipstick[R]. The general trends observed in these figures are more succinctly reflected in Figure 15, which shows simple bar representations of the relative degree of correlation with the Dipstick[R] for each instrument and sampling rate. Here, it would appear that the strongest relationship with the Dipstick[R] is demonstrated by the ultrasonic-based equipment sampling at 240 mm (0.8 foot) intervals.

Figure 16, which charts the average instrument *differences* at the varying sampling rates, is somewhat contradictory to the correlation analysis just discussed. It indicates that the best agreement with the Dipstick[R] was given by the lasers, which improved dramatically as the sampling interval was reduced from 4 to 2 (240 to 120 mm, respectively). More specifically, the *difference* between the lasers and the Dipstick[R] at the smaller sampling interval was approximately one fifth of its value at larger sampling intervals. These average differences also indicate that a convergence of sorts took place between the two alternative height sensing devices at the lower sampling resolution (rate 6). That is, this chart also appears to suggest that the ultrasonics' agreement with the Dipstick[R] improved as sampling resolution decreased, or sampling interval increased.
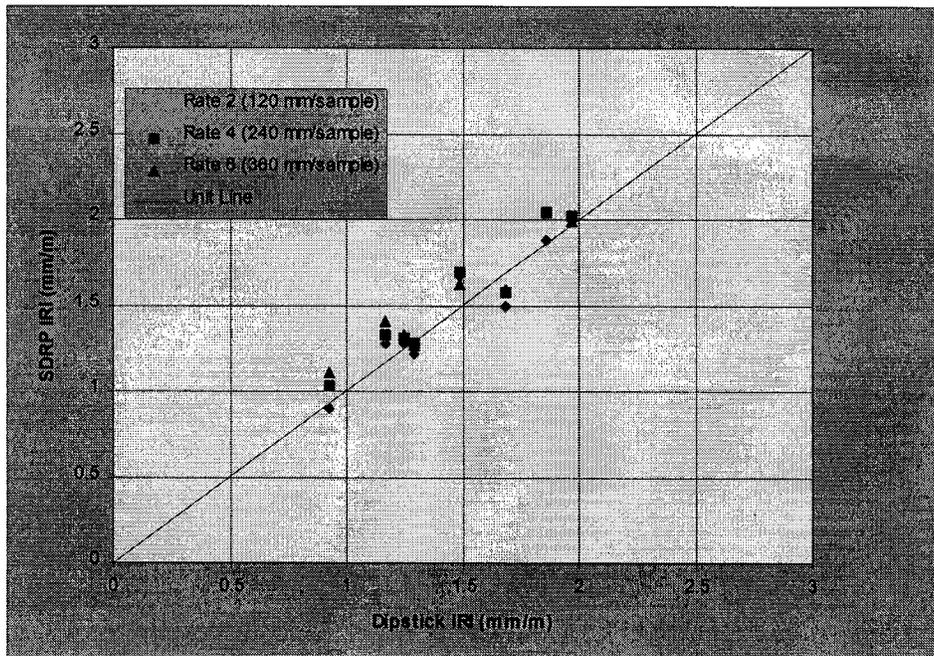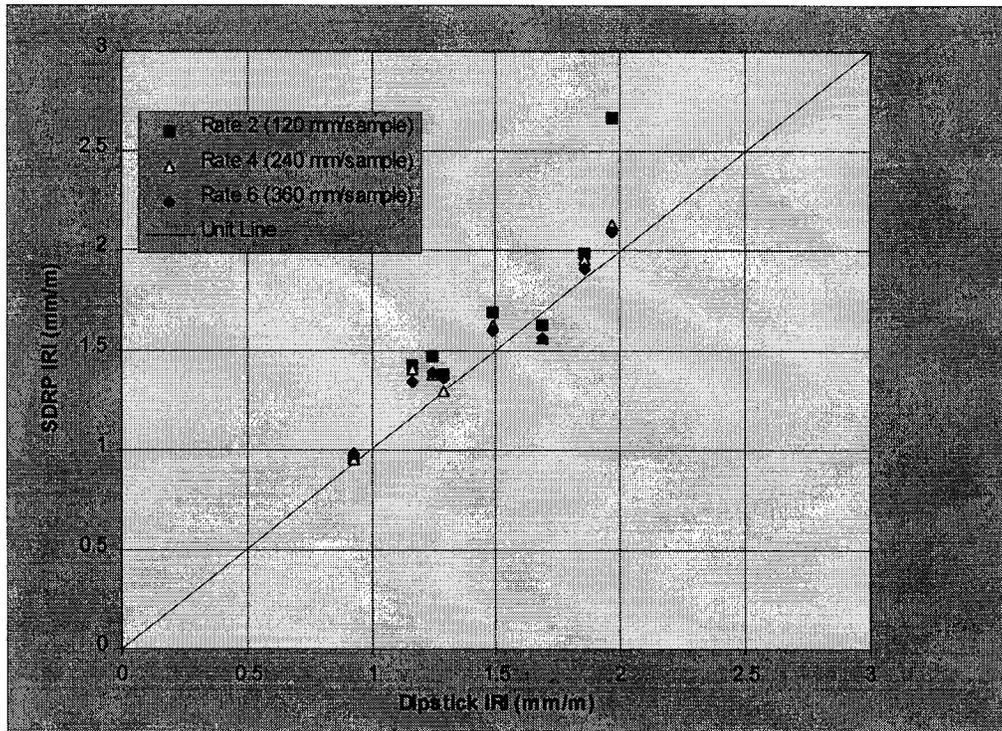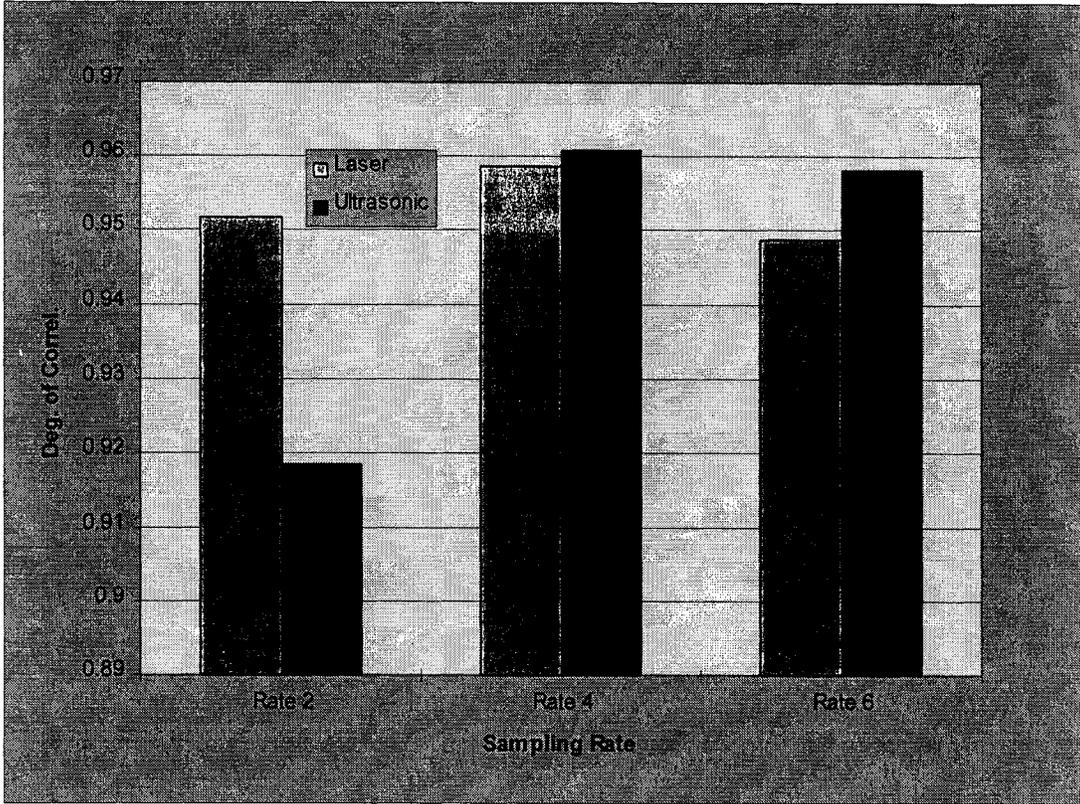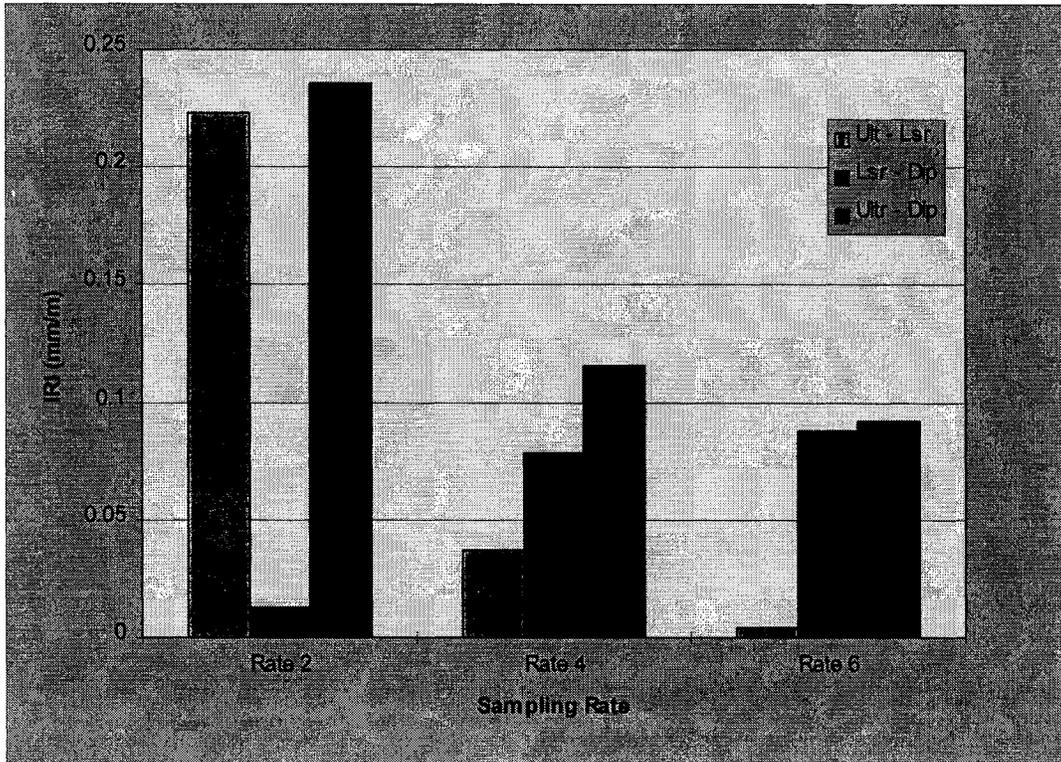
16

Figure 13. Laser-based IRI

Figure 14. Ultrasonic-based IRI

Figure 15. Correlation with Dipstick

Figure 16. Average Instrument Difference

18

Speed

The approach taken to evaluate the relative performance of ultrasonic and laser height sensors at varying vehicle speeds was much the same as that used to assess the effects of sampling rate. Once again, scatter plots for each speed were prepared, as in Figure 17 and Figure 18. These plots were supplemented by a correlation analysis, the results of which are summarized in Figure 19. The best performance, again as determined through correlation with the Dipstick[R], was returned by the ultrasonics sensors operated at 48 and 64 kilometers per hour (30 and 40 mph). In fact, on average, the ultrasonics demonstrated a higher degree of correlation than the laser at every speed tested.
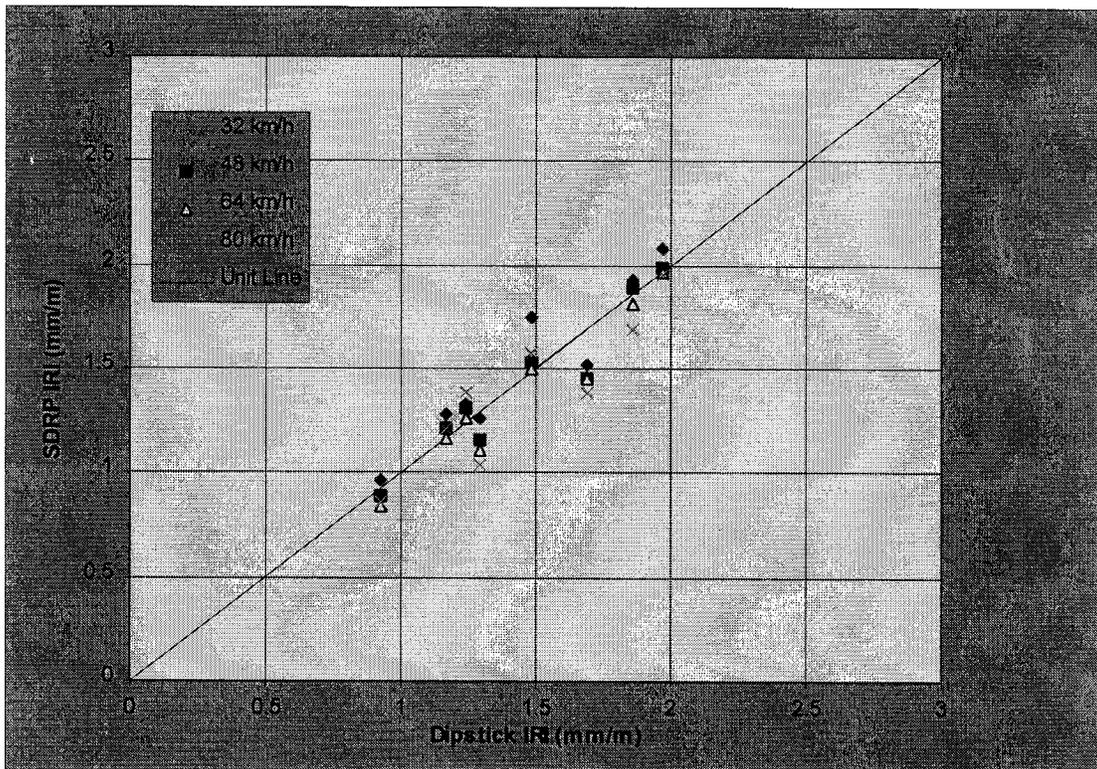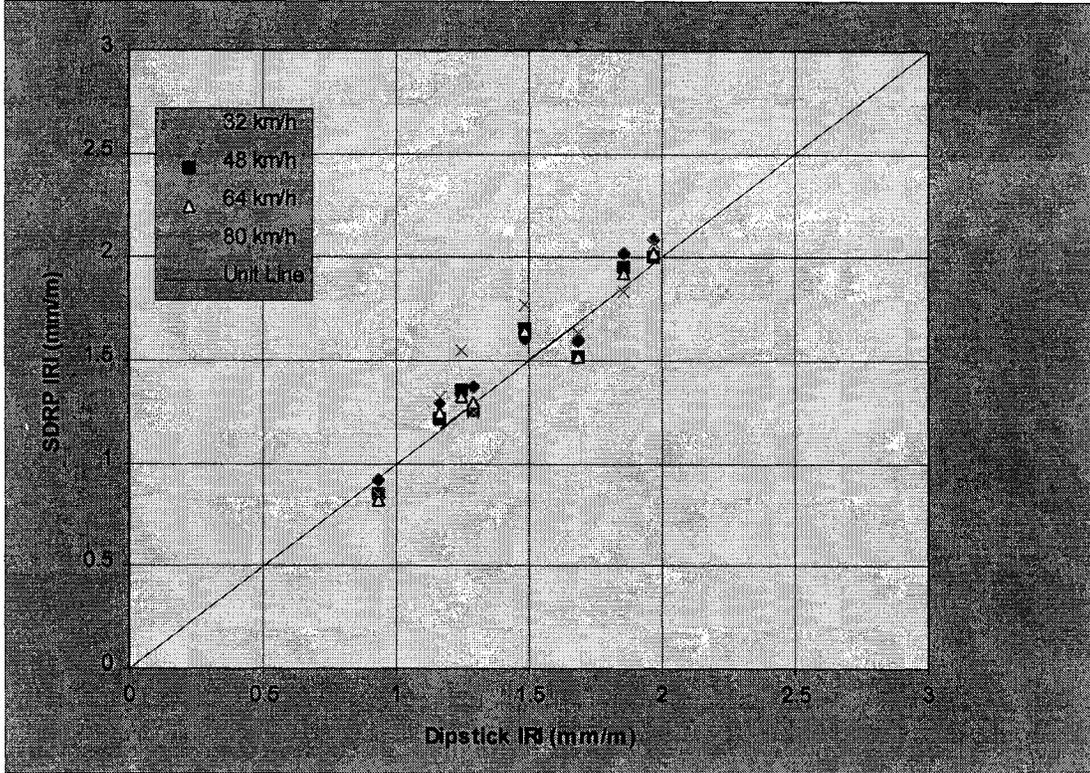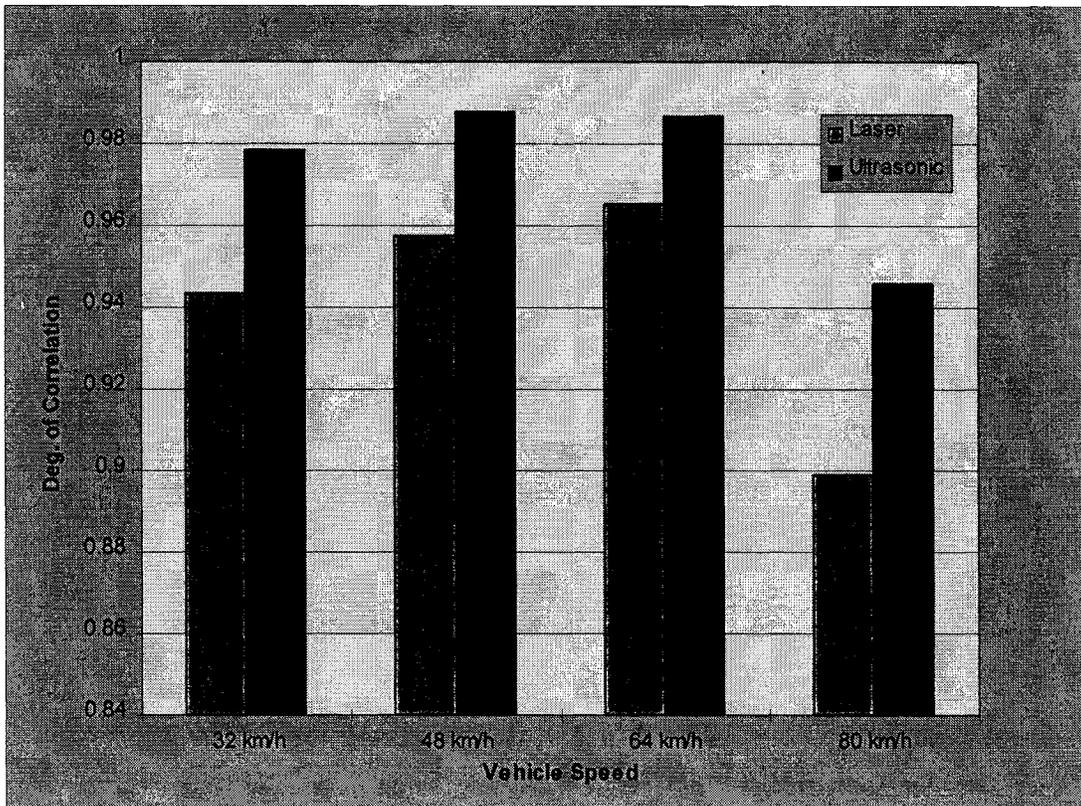

Figure 17. Laser-based IRI

19

Figure 18. Ultrasonic-based IRI

Figure 19. Correlation with Dipstick

This series of tests also suggested that an increase in collection speed was accompanied by an increased disagreement between the Dipstick[R]-based IRI and that estimated by the SDRP. As speed was increased to 80 kilometers per hour (50 mph), the ultrasonic-based roughness tends to creep up with respect to data based on the Dipstick[R] (Figure 20). The opposite effect was noted with the laser instruments, which tended to underestimate roughness at higher speeds. The bar chart depicting the difference between estimated ultrasonic and laser roughness shows an almost perfectly linear increase with the increase in the collection vehicle speed. Figure 21 represents a correlation analysis comparing instrument difference and speed. Through this analysis, a positive correlation coefficient of nearly unity was observed between speed increase and the difference in IRI between ultrasonics and lasers. As collection speed increased, either the ultrasonic roughness increased with respect to laser roughness or the laser roughness decreased with respect to the ultrasonics. The same chart indicated a fairly strong negative correlation between laser roughness and that based on the Dipstick[R]. Surprisingly, any correlation between speed change and the difference between ultrasonic and Dipstick[R] roughness appeared negligible. This suggests that the laser equipment was indeed exhibiting a sensitivity to speed; as speed increased, the laser-based system consistently underestimated the roughness. From that, it may be surmised that the apparent correlation between the ultrasonics and lasers was due almost exclusively to a sensitivity of lasers to speed.
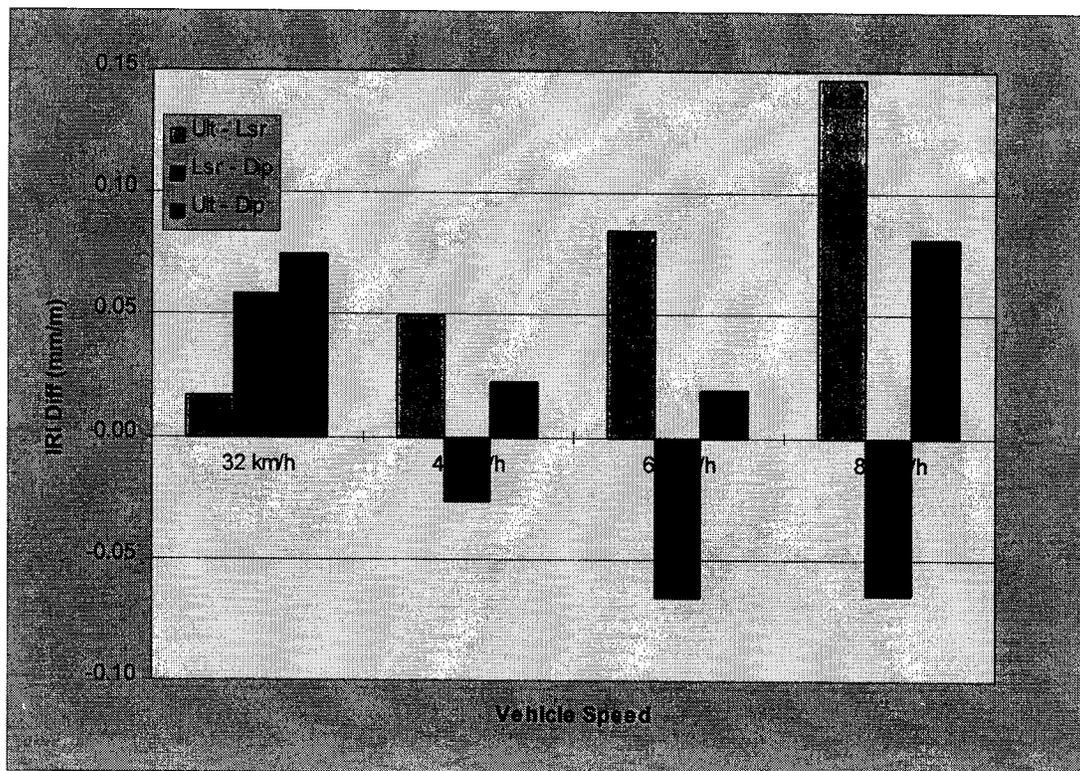
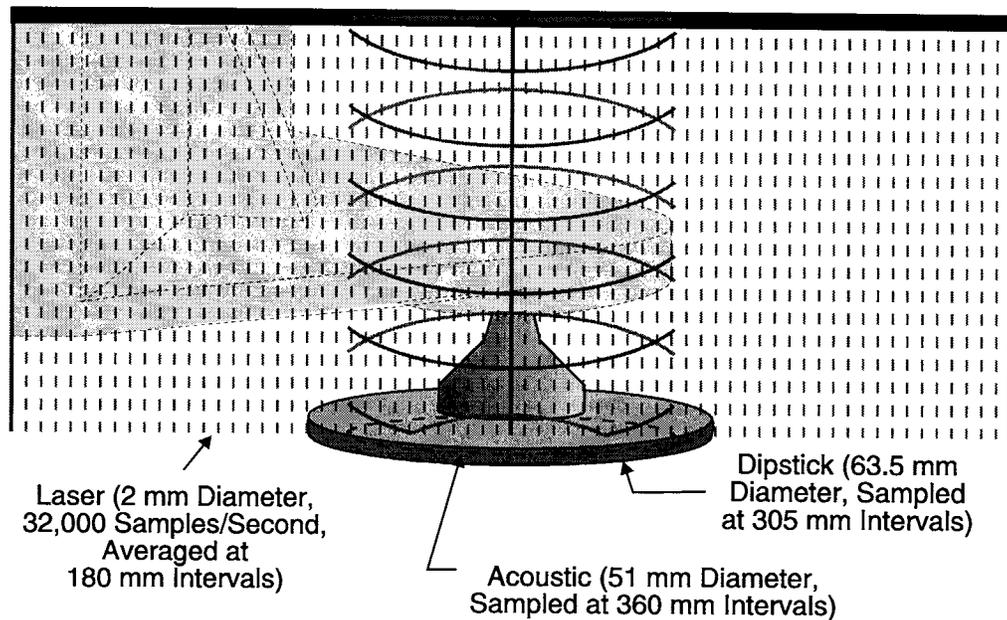**Figure 20. Average Instrument Difference**

21
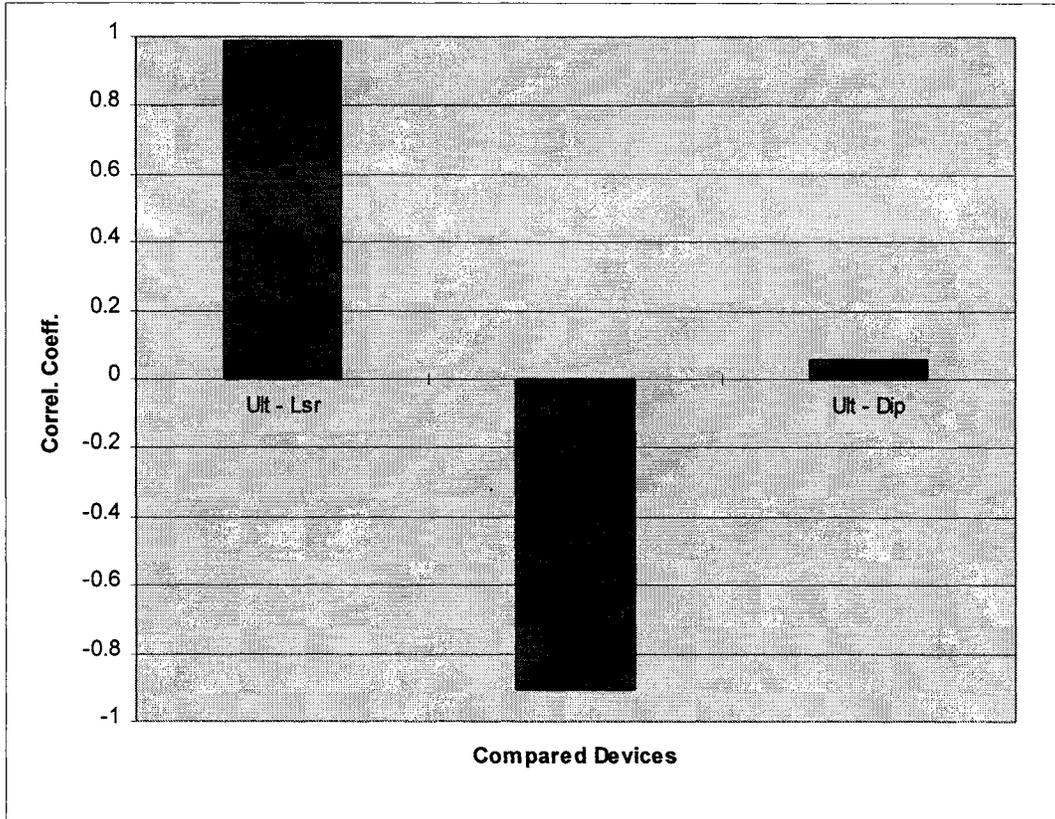
Figure 21. Correlation of Equipment Difference and Speed

DISCUSSION

Under the conditions at which these tests were conducted, both height sensing devices performed well, compared to one another and to the control information.

Device Footprint Comparison

A closer look at the physical details of the sampling procedures used by the respective instruments may provide some explanation for the surprisingly good performance registered by the ultrasonics, particularly as compared to the Dipstick[R] (Figure 22). First, the footprint of the ultrasonic device, albeit a sound wave-front instead of a circular metal disk, is more nearly on the same order of magnitude, size-wise, as the Dipstick[R]. While the size of the Dipstick[R] "moon" feet are 64 mm (2 1/2 in) and the ultrasonic transducer's footprint on the surface is about 50 mm (2 in), the Selcom infrared laser beam measures only about 2 mm (0.08 in) in diameter.

22

Laser (2 mm Diameter, 32,000 Samples/Second, Averaged at 180 mm Intervals)

Acoustic (51 mm Diameter, Sampled at 360 mm Intervals)

Dipstick (63.5 mm Diameter, Sampled at 305 mm Intervals)

**Figure 22. Sensor Footprint Comparison**

In addition to footprint size, the method of sampling and recording the surface profile with the Dipstick^R is more like that used by the ultrasonic height sensors than the lasers. Both the Dipstick^R and the ultrasonic devices measure the profile in discrete steps. The lasers, on the other hand, collect data continuously, storing average heights at the specified intervals of distance. Theoretically, the lasers "miss" less surface than either the ultrasonics or the dipstick. Conversely, the Dipstick^R and the ultrasonic sensors may not see as much roughness as the lasers. By the same token, there are cases where the resolution of the lasers can theoretically identify more roughness than is actually relevant.

Finally, as the tests cycled through varying sampling rates, those tests with intervals most closely resembling the 300 mm (1.0 foot) Dipstick^R foot spacing returned the highest degree of correlation. The laser sampling rate that correlated best was at a sampling interval of 240 mm (slightly less resolution than routinely used with laser roughness measurements).

Instrument Reliability

An issue that had not been targeted for formal investigation, but which has proven to be critical, is relative hardware reliability. Unfortunately, failures and malfunctions of ultrasonic sensor units have become fairly routine. In fact, between June 1993 and September 1994 records kept by the NDT unit show that at least 6 sensor repairs (at $275 each) were necessary. For some of this time period, there was only one pure ultrasonic SDRP vehicle in operation. For the period of time that covered the 1995 spring-summer-fall construction season, the number of ultrasonic repairs necessary was at least as high.

Periodic sensor failure is certainly not desirable. However, a more perplexing, and potentially detrimental difficulty surfaced later in the 1995 construction season. Data collection in support of a related study had begun when the operators first noticed that the left wheel path (LWP) roughness, as measured by the LWP ultrasonic sensor, was starting to drift up and away from the laser-based readings. This occurred without warning from the built-in hardware or software checks and would likely have continued unnoticed for some time, had there not been accompanying laser information. The problem persisted until the operator had replaced the sensor three times, implying that the difficulty may be a problem with the system in general, and not necessarily due to a malfunctioning sensor. During fall repeatability work, the drift in ultrasonic roughness was again observed. This time, however, the phenomenon was present and very obvious in the right wheelpath. Data available from spring surveys of the same section (when all sensors were functioning properly) indicated that there was indeed more roughness in the right wheelpath than the left. In the spring, the difference between ultrasonic and laser roughness in the right wheelpath (RWP) was 13 percent, while the LWP difference was a little over 9 percent. With the suspected malfunctioning sensor in the fall surveys, the LWP difference was still just past 5%. The RWP discrepency had more than doubled to 27 percent. Figure 23 illustrates that out of the ten runs conducted in the fall test, the right wheelpath roughness (as estimated using ultrasonic-based profiles) was obviously overestimated in at least eight.
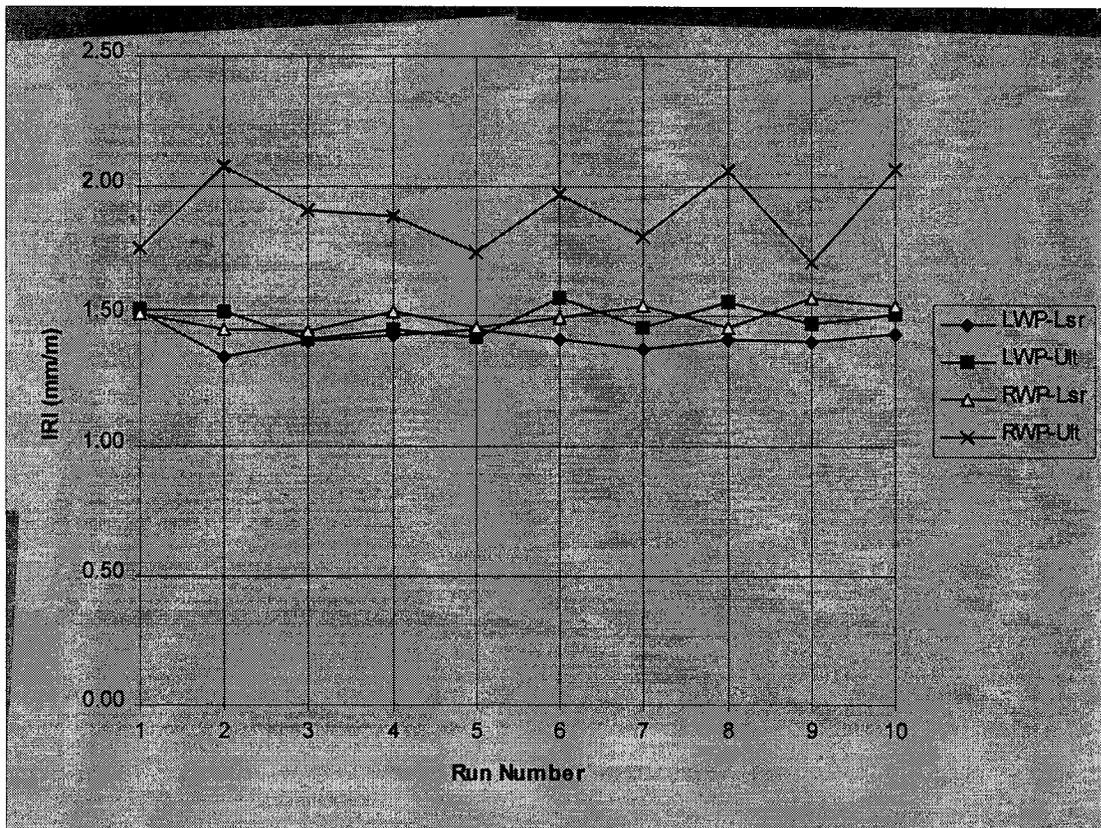
Figure 23. Sensor Malfunction

24

Obviously, a malfunction of this nature could have been disastrous had it occurred while administering rideability specifications with pure ultrasonic instruments. Hardware reliability may be the most compelling reason to migrate to pure laser roughness measurement.

CONCLUSIONS

The majority of the tests described herein were conducted under conditions that are generally considered ideal for ultrasonic profilers. The weather was dry, temperatures moderate, and pavement surfaces fairly mundane. Unfortunately, these tempered conditions fail to expose the equipment to those ambient scenarios where the laser instruments would likely have performed best by comparison. For example, experience has shown that the slightest misting of precipitation will generally incapacitate ultrasonics, while anecdotal experiments have failed to register any reaction from the lasers. Previous research has also shown that temperature extremes can contribute to erratic results with ultrasonic sensors.[4] Theoretically, fluctuations in temperature have no effect on lasers.

The findings from this study support the following conclusions:

1. Laser-based roughness measurement is more repeatable than ultrasonic-based measurement.
2. At most sampling rates and vehicle speeds, ultrasonic-based roughness measurements correlate with the Dipstick[R] as well or better than laser-based.
3. However, over a range of surfaces, laser-based numbers differ less from the Dipstick[R] than ultrasonics, and the difference decreases with increased sampling resolution (with speed held constant).
4. Estimated laser-based IRI decreases as speed increases (especially as speeds are increased from below 64 km/h).
5. Laser instruments were more reliable than ultrasonics.

RECOMMENDATIONS

If current trends continue, VDOT's network roughness surveying will soon be conducted almost exclusively by private contractors. This will not, in the author's opinion, eliminate the need for VDOT to maintain the technical expertise and physical capacity to ensure that the State continues to receive quality information.

In more specific terms, the following recommendations are offered:

1. *Use ultrasonic devices carefully for network level surveying where all surfaces are reasonably similar and more localized assessments are not expected.* A strict calibration regiment is imperative. The reliability issue, which in many cases is associated with moisture, may make ultrasonic-based equipment more practical in dry, moderate climates (not necessarily Virginia).
2. *Use laser devices for all other types of network level surveying, especially when the network includes a broad range of surface types.* Moreover, it is the opinion of the author that any future network surveys conducted or authorized by VDOT should avoid ultrasonic sensors and instead specify a laser preference.
3. *Use laser devices for any work conducted at the project level.* Actually, the suitability of a given SDRP for project level work is most dependent on the accuracy and calibration of the distance measuring equipment, along with the ability of the hardware and software to synchonize instruments. This research has shown, however, that the data collected with the lasers are generally more repeatable and thus, more appropriate for use where detail is critical.
4. *Lastly, it is strongly suggested that VDOT migrate to pure laser-based SDRP equipment.* It is likewise recommended that any additional SDRP systems, purchased or leased by The Department, be equipped with laser-type height sensors.

FUTURE RESEARCH

There has been much discussion regarding the potential use of the SDRP for establishing and administering smoothness specifications for maintenance overlays. A draft specification has been developed and work in support of it already informally initiated. It is suggested that continued research in the road profiling program be devoted to formal support of the overlay ride quality specification. Numerous obstacles threaten the successful implementation of this specification. Not the least of these obstacles is a shared uncertainty regarding the many factors that influence the achievable smoothness of an overlay. A non-comprehensive list of issues that likely affect the rideability of a new asphalt overlay include:

- the ride quality of the overlaid pavement
- the predominant distress of the overlaid pavement
- the mix type and thickness
- the surveyed age and cummulative traffic loadings
- the experience and skill level of a contractor's crew
- the types and condition of the contractor's equipment
- the placement rate maintained by a contractor.

An understanding of how these types of variables influence the ride quality of overlays would be invaluable to public officials, the contracting industry, and highway users.

ACKNOWLEDGEMENTS

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