STATE OF FLORIDA

A COMPARISON OF ROUGHNESS MEASUREMENTS FROM LASER AND ULTRASONIC ROAD PROFILERS

Research Report
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STATE MATERIALS OFFICE

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ABSTRACT

The Florida Department of Transportation has recently converted all of its road profilers from ultrasonic to laser. This conversion aimed at obtaining more reliable and accurate instruments for measuring pavement roughness. These roughness measurements are normally utilized as part of the Florida DOT Pavement Management System to develop pavement investment strategies. As part of the conversion process, several field studies were performed to compare the old ultrasonic and the new laser profilers. The studies aimed at determining the differences in roughness measurements due to the conversion from ultrasonic to laser sensors. In addition, There was an interest in determining if roughness measurements in different wheel paths are equal. Finally, the effect of the typical 300 ft filtering of data was evaluated.

Over 1,500 Kilometers of typical pavement sections were included in the experiment. These sections were tested with the ultrasonic as well as the laser road profilers. A comprehensive statistical analysis was later performed on the data. This analysis showed some significant differences in roughness measurements due to sensor type and location. In addition, it was found that data filtering does not have any influence on the ultrasonic measurements. However, filtering will make laser measurements significantly smoother.

This paper summarizes the above findings. In addition, the paper provides valuable technical information which is useful for other states in the process of converting to laser profilers.

INTRODUCTION

Road roughness is an important factor in evaluating the condition of a pavement section because of its effects on ride quality and vehicle operating costs. In its broadest sense, road roughness has been defined as "the deviations of a surface from a true planar surface with characteristic dimensions that affect vehicle dynamics, ride quality, dynamics loads, and drainage"[1]. Despite this broad description, the practice today is to limit the measurement of roughness qualities to those related to the longitudinal profile of the road surface which cause vibrations in road-using vehicles.

In general, road roughness can be caused by any of the following factors [2]:

a. Construction techniques which allow some variation from the design profile.
b. Repeated loads particularly in channelized areas.
c. Frost heave and volume changes due to shrinkage and swell of the subgrade.
d. Non-uniform initial base or subgrade compaction.

In the last three decades, several studies pointed out the major penalties of roughness to the user. In 1960, Carey and Irick[3] showed that the driver's opinion of the quality of serviceability provided by a pavement surface is primarily influenced by roughness. Between 1971 and 1982, the World Bank supported several research activities in Brazil, Kenya, the Caribbean, and India. The main purpose of these studies was to investigate the relationship between road roughness and user costs. In 1980, Rizenbergs[4] pointed to the following penalties associated with roughness: rider non-acceptance and discomfort, less safety, increased energy consumption, road-tire loading and damage, and vehicle deterioration.

BACKGROUND

Over the years, pavement roughness measuring devices improved with new technological discoveries. The earliest form of roughness measuring device was a straightedge which was used to measure pavement variations. Other devices were later developed including: rolling straightedges, profilographs, response-type road-roughness-measuring systems, and profilometers. Each new device incorporated some improvements over the earlier measuring devices. Such improvements included: speed of operation, accuracy, repeatability, or a combination of these factors [6]. Today, most state DOT's utilize various types of profilometers in measuring pavement roughness. Some DOT's are still using ultrasonic based road profilers due to their low prices. Other states have started converting their ultrasonic based road profilers to laser profilometers to improve data accuracy.

The Florida Department of Transportation (FDOT) has recently converted all of its five road profilers from ultrasonic to laser. This important task was performed in two stages. The first stage concentrated on converting only one unit to laser in 1997 and then performing various comprehensive studies to determine the effect of conversion to laser on roughness measurements. After evaluating these effects, the rest of the road profiler units were converted to laser early in 1998. This paper summarizes the major findings from the comparison between laser and ultrasonic road profilers. In addition, the paper provides useful information to those states in the process of converting to laser based road profilers.

LASER VERSUS ULTRASONIC ROAD PROFILERS

Early in 1997, the Florida Department of Transportation upgraded one of its International Cybernetics Corporation's (ICC) ultrasonic profilers to a hybrid system using both ultrasonic and laser sensors to monitor ride and rut depth. The laser sensors are more accurate than ultrasonic sensors for measuring profiles since they are less likely to be affected by temperature, pavement texture, moisture, etc. In addition, the laser sensors fire 32,000 times per second and average these measurements every one foot. The ultrasonic sensors fire approximate once every foot at fifty-five miles per hour.

The upgrade to a hybrid system was done by ICC in a two-week time frame. The cost of the conversion was about $50,000 per unit. In addition to the conversion from ultrasonic to laser sensors, other enhancements were added to the FDOT road profilers. These enhancements included: a Distance Measuring Instrument (DMI) located on the vehicle's dashboard to make it visible to the driver. In addition, an automated triggering device was added to start and stop data collection by activation from reflective tape on pavement surfaces.

DESIGN OF EXPERIMENT

The comparison between laser and ultrasonic road profilers was performed to address the following important points:

a. Determining the differences in IRI measurements in both wheel paths. FDOT currently measures roughness in the right wheel path only. The conversion from ultrasonic to laser provided a good opportunity to determine if measurements should include both wheel paths.

b. Evaluating the effect of 300 ft filtering on the roughness data collected with both ultrasonic and laser road profilers.

c. Determining if laser based road profilers will produce IRI measurements equal to those produced over the years with the FDOT ultrasonic profilers.

In order to provide answers for the above questions, roughness data was collected on several representative sections in the state of Florida with both ultrasonic and laser based road profilers. These roughness measurements were processed for each wheel path. In addition, IRI values were calculated with and without the 300 ft filtering to determine the effect of filtering on IRI measurements. The data collected was then summarized in a comprehensive computerized data base and then statistically analyzed.

DATA COLLECTION

The Florida Department of Transportation collect roughness measurements on about 29,000 Kilometers (18,000 miles) every year. In this study, both the ultrasonic and laser profilers were used to collect data on all pavement sections in the following three counties: Alachua, Clay, and Marion counties. Three hundred and forty-two sections that had been tested using Ultrasonic Profilers as part of the Pavement Condition Survey were tested again using the Laser Profiler. The rated sections varied in length and exhibited a wide range of roughness values typical of those found in Florida. The total length of the sections included in the experiment was about 1,500 Kilometers (932 Miles) which provided a good sample size for the analysis.

DATA ANALYSIS

The primary objective of the statistical analysis was to compare IRI measurements obtained with the ultrasonic and laser road profilers. The secondary objective was to determine the effect of filtering and wheel path selection on the measured IRI values. In order to fulfill these objective, IRI's with laser and ultrasonic profilers were calculated for left wheel path, right wheel path, and average wheel paths on all test sections included in the experiment. In addition, IRI values were determined with and without 300' filtering. After obtaining the necessary data, the statistical analysis was performed on the data. This analysis included first generating some descriptive statistics and then performing the single factor Analysis of Variance (ANOVA). Finally, IRI measurements obtained based on the various methods were correlated statistically. The following sections described the various analysis performed in this study.

a. Results from The Descriptive Statistics:

Some descriptive statistics were obtained on all the data sets included in this study. As shown in Table 1, the average IRI values obtained with laser sensors were always less than those obtained with ultrasonic sensors. It is also clear from Table 1 that the filtered IRI values were less than unfiltered values. Furthermore, IRI values in the right wheel path were higher than those in the left wheel path. When looking at the maximum and minimum IRI values measured in each wheel path, it is clear that the right wheel path showed significantly wider variations than the left wheel path.

b. Results from The ANOVA Analysis:

After considering these visual observations, the single factor Analysis of Variance (ANOVA) was performed to determine if the differences in IRI values are significant statistically. Table 2 summarizes the results from this analysis. In this analysis, the calculated F values should be less than the critical F value in order to conclude that the data sets are equal statistically. It is clear from table 2 that for ultrasonic sensors: left, right, and average wheel path IRI values were statistically different at $\alpha = .05$. For laser sensors, left and right wheel path values were statistically different. However, both wheel path measurements were statistically equal to the average values. The worst comparisons were between laser and ultrasonic IRI values where the F values became very high indicating significant differences.

A similar analysis was performed on the data to determine the effect of filtering on IRI values. Table 3 summarizes the finding from that analysis. In all cases except one, the filtering of the data from resulted in significantly reducing IRI values. Even for the right laser sensors, the equality of filtered and unfiltered data is shaky because the calculated F of 3.6 is very close to the critical F of 3.86. Therefore, it is concluded that filtering will result in significantly reducing roughness values.

c. Results from The Correlation Analysis:

It was clear from the ANOVA analysis performed that sensor type, location, and filtering will result in producing variable IRI values. The next step in this analysis was to determine if these IRI values can be statistically correlated. Correlation factors were obtained on all possible combinations. Table 4 summarizes these correlation factors which ranged from .75 to 1 indicating that although sensor type, location, and filtering will result in statistically different IRI values, these IRI values are very well correlated. Figure 1 shows the scattered point diagram for IRI measurements obtained with the right and left wheel paths of ultrasonic profilers. It is clear from this figure that most of the points fell above the equality line indicating that the right wheel path IRI values are higher than the left wheel path values. Despite of these differences, the following regression equation was developed to correlate the two with R Square of 0.82:

$$IRI_{left} = 16.5 + 0.7 * IRI_{right}$$

Where:

IRI_{left}: IRI in the left wheel path.
IRI_{right}: IRI in right wheel path.

A similar graph, Figure 2, was developed to compare IRIs from the laser and ultrasonic road profilers. This graph shows how the laser measurements were less than the ultrasonic measurements for most sections included in the experiment. The following regression model was developed to correlate ultrasonic and laser measurements:

$$IRI_{laser} = 16.5 + 0.7 * IRI_{ultrasonic}$$

Where:

IRI_{laser}: IRI from laser road profiler.

$IRI_{ultrasonic}$: IRI from ultrasonic road profiler.

The R Square of the above regression model was 0.75. Similar regression relationships could be developed for any other factors of interest.

CONCLUSIONS

The following conclusions can be drawn based on the analysis performed in this study:

a. Sensor location does affect the resulting IRI values. Right wheel path sensors tend to result in significantly higher IRI values than left wheel path sensors. This is true for both ultrasonic and laser sensors. In addition, the range of IRI values in the right wheel path is much wider than the left wheel path.

b. Sensor type whether ultrasonic or laser will affect IRI measurements. Laser sensors produce significantly smaller IRI values than ultrasonic sensors. This is due to the better accuracy of the laser sensors in addition to the averaging of several measurements per foot. Therefore, if an agency is considering the conversion from ultrasonic to laser, they should be aware that the switch will result in smaller roughness numbers. An adjustment should be made to any rehabilitation strategies that are based on those roughness measurements.

c. Measurements obtained in different wheel paths and by using different sensors are highly correlated. The highest correlations are obtained when comparing laser to laser sensors. The worst correlations are obtained when comparing laser and ultrasonic sensors.

d. Data filtering at 300 ft will significantly affect the IRI measurements obtained from both ultrasonic and laser road profilers.

RECOMMENDATIONS

The following recommendations are made:

a. There should be specific national guidelines for collecting roughness data for the HPMS. Currently, states are collecting data by using different devices, the data is collected in different wheel paths, and some states are filtering the data while others are not. This study showed clearly how all of these factors will result in significant variations in the roughness data reported.

b. Florida DOT should continue using roughness data from the right wheel path until national guidelines have been developed. Using the right wheel path will result in more conservative roughness values.

c. The data obtained with the new laser profilers should be filtered at 300 ft. It should be kept in mind that this filtering will result in smoother measurements.

The combination of converting to laser profiler and filtering will result in producing lower IRI values.

ACKNOWLEDGMENT

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REFERENCES

1. Sayers, M. W., "Development, Implementation, and Application of The Reference Quarter-Car Simulation", ASTM Special Technical Publication 884,1985.

2. Yoder, E. J., Hampton D., "Pavement Profile and Roughness Measurements; A Review of Method", Purdue University, January, 1958.

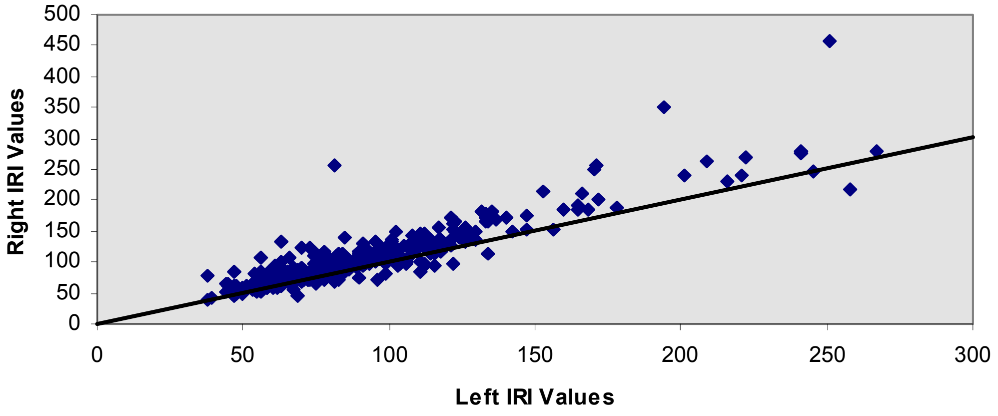
3. Carey, W. N., and Irick, P. E., "The Pavement Serviceability- Performance Concept", HRB, Bull. 250, 1960, pp. 40-58.

4. Rizenbergs, R. L., "Roughness Of Pavements (An Overview)", Kummer Lecture, Presented to ASTM Committee E-17 On Traveled Surface Characteristics, Orlando, FL., 10 Dec. 1980.

5. Janoff, M. S., "The Relationship between Initial Pavement Smoothness and Long-Term Pavement Performance", TRB Committee A2B07, Washington, DC January 1990.

6. Woodstrom, J. ."Measurements, Specifications, and Achievement of Smoothness for Pavement Construction", NCHRP Report 167, 1990.

Figure 1. IRIs from The Left and Right Wheel Paths of The Ultrasonic Road Profilers.



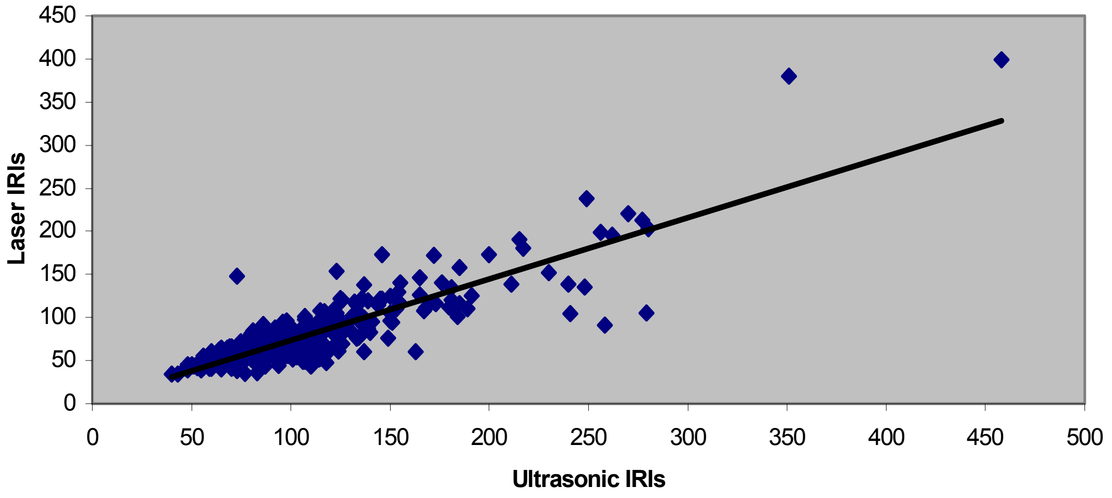


Figure 2. IRIs from Laser and Ultrasonic Road Profilers.

Table 1. Descriptive Statistics of The Various Data Sets

DATA SET	FILTERED	MEAN	MINIMUM	MAXIMUM	RANGE
ULWP	NO	91	37	246	209
URWP	NO	107	43	462	419
UAWP	NO	99	42	354	312
ULWP		83	33	230	197
URWP	YES	98	40	436	396
UAWP	YES	97	39	355	316
LLWP	NO	75	35	251	216
LRWP	NO	83	37	427	390
LAWP	NO	79	36	339	303
LLWP	YES	69	32	234	202
LRWP	YES	77	34	399	365
LAWP	YES	73	33	317	284

NOTE:
ULWP = ULTRASONIC LEFT WHEEL PATH
URWP = ULTRASONIC RIGHT WHEEL PATH
UAWP = ULTRASONIC AVERAGE WHEEL PATHS
LLWP = LASER LEFT WHEEL PATH
LRWP = LASER RIGHT WHEEL PATH
LAWP = LASER AVERAGE WHEEL PATHS

Table 2. Results from The ANOVA Analysis.

FACTORS COMPARED		**FILTERED**	**F_{CRIT}**	**F**	**RESULTS**
ULWP	URWP	NO	3.86	27.19	DIFFERENT
ULWP	URWP	YES	3.86	28.20	DIFFERENT
URWP	UAWP	NO	3.86	6.07	DIFFERENT
URWP	UAWP	YES	3.86	6.23	DIFFERENT
ULWP	UAWP	NO	3.86	8.50	DIFFERENT
ULWP	UAWP	YES	3.86	8.96	DIFFERENT
LLWP	ULWP	NO	3.86	40.60	DIFFERENT
LRWP	URWP	NO	3.86	45.80	DIFFERENT
LAWP	UAWP	NO	3.86	45.90	DIFFERENT
LLWP	ULWP	YES	3.86	37.71	DIFFERENT
LRWP	URWP	YES	3.86	41.33	DIFFERENT
LAWP	UAWP	YES	3.86	41.81	DIFFERENT
LLWP	LRWP	NO	3.86	8.59	DIFFERENT
LLWP	LRWP	YES	3.86	9.90	DIFFERENT
LRWP	LAWP	YES	3.86	2.16	EQUAL
LRWP	LAWP	NO	3.86	1.88	EQUAL
LLWP	LAWP	NO	3.86	2.71	EQUAL
LLWP	LAWP	YES	3.86	3.13	EQUAL

NOTES:
ULWP = ULTRASONIC LEFT WHEEL PATH
URWP = ULTRASONIC RIGHT WHEEL PATH
UAWP = ULTRASONIC AVERAGE WHEEL PATHS
LLWP = LASER LEFT WHEEL PATH
LRWP = LASER RIGHT WHEEL PATH
LAWP = LASER AVERAGE WHEEL PATHS

Table 3. A Comparison between Filtered and Unfiltered Data.

FACTORS COMPARED		F_{CRIT}	**F**	**RESULTS**
ULWP	ULWP	3.86	10.00	DIFFERENT
URWP	URWP	3.86	6.05	DIFFERENT
UAWP	UAWP	3.86	8.05	DIFFERENT
LLWP	LLWP	3.86	7.81	DIFFERENT
LRWP	LRWP	3.86	3.60	EQUAL
LAWP	LAWP	3.86	5.31	DIFFERENT

NOTES:
ULWP = ULTRASONIC LEFT WHEEL PATH
URWP = ULTRASONIC RIGHT WHEEL PATH
UAWP = ULTRASONIC AVERAGE WHEEL PATHS
LLWP = LASER LEFT WHEEL PATH
LRWP = LASER RIGHT WHEEL PATH
LAWP = LASER AVERAGE WHEEL PATHS

Table 4. Correlation Coefficients Among The Different Data Sets Included in The Experiment.

			LINEAR REGRESSION CORRELATION FACTORS											
			ULTRASONIC						**LASER**					
			NOT FILTERED			**FILTERED**			**NOT FILTERED**			**FILTERED**		
			LWP	**RWP**	**AWP**	**LWP**	**RWP**	**AWP**	**LWP**	**RWP**	**AWP**	**LWP**	**RWP**	**AWP**
ULTRASONIC	**NOT FILTERED**	**LWP**												
		RWP	0.88											
		AWP	0.96	0.98										
	FILTERED	**LWP**	0.91	0.89	0.96									
		RWP	0.87	1.00	0.97	0.89								
		AWP	0.95	0.98	1.00	0.96	0.98							
LASER	**NOT FILTERED**	**LWP**	0.83	0.83	0.85	0.85	0.84	0.87						
		RWP	0.76	0.88	0.85	0.79	0.89	0.87	0.93					
		AWP	0.80	0.87	0.87	0.82	0.88	0.88	0.98	0.99				
	FILTERED	**LWP**	0.82	0.83	0.85	0.85	0.84	0.87	1.00	0.94	0.98			
		RWP	0.75	0.87	0.85	0.78	0.89	0.87	0.93	1.00	0.99	0.94		
		AWP	0.79	0.87	0.86	0.82	0.88	0.88	0.98	0.99	1.00	0.98	0.99	

NOTES:
LWP = LEFT WHEEL PATH
RWP = RIGHT WHEEL PATH
AWP = AVERAGE OF BOTH WHEEL PATHS