Final Report 930-371

EVALUATION OF PAVEMENT SMOOTHNESS REDUCTION AND PAY FACTOR DETERMINATION FOR ALABAMA DEPARTMENT OF TRANSPORTATION

Prepared by

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MARCH 2002

Final Report

on

Alabama Department of Transportation
Research Project 930-371

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CHAPTER 1. INTRODUCTION

Pavement smoothness, alternately called roughness, is a measure of the riding quality that is frequently used to describe how well a pavement has been constructed. For many years ride quality of a roadway surface was generally not measured and a pavement was deemed acceptable if it could be traveled. As vehicle volumes and speeds increased the need for quality pavements became a necessity. Not only was ride quality important to satisfy its users, many other benefits began to be foreseen as well. Producing smooth pavements increases ride quality, reduces fuel consumption, maintenance costs, vehicle wear, and increases road safety. Studies have also shown that achieving smoothness at the initial construction stage of the pavement extends the life of the pavement by reducing dynamic wheel loads, particularly from large trucks, that were a function of excess roughness. As a result of these economic and safety concerns, many State Highway Associations have developed specifications requiring contractors to meet a specified level of pavement smoothness upon construction.

Many state Departments of Transportation use the California type mechanical profilograph to evaluate pavement smoothness. The mechanical profilograph is a wheeled device that is moved along the roadway measuring the magnitude of the high and low deviations from a level surface. The California type of profilograph records these deviations on a continuous roll of paper called a profilograph trace.

The manual method has been the predominant method of reducing the profilograph traces. It consists of centering a specially ruled instrument, called a blanking band, on the trace and then counting the number of deviations, termed scallops, beyond a specified limit to produce a pavement roughness index (PRI). Experience of the evaluator, discretion with the proper positioning of the blanking band and difficulty in accurately measuring scallops results in considerable variation in the smoothness measures. Studies by the Arizona Transportation Research Center indicate that the results of the manual analysis can differ as much as 6 inches per mile between different analysts and between different observations by the same analyst for a smooth section of pavement. Rough sections of pavement resulted in differences of as much as 9 inches per mile between two readings. The wide variability in the manual method leads to questions of its dependability for acceptance testing of pavements.

Efforts to reduce the problems associated with manual reduction of profilograph traces have resulted in a computerized profilograph and electronic scanning alternatives. The computerized version of the California profilograph electronically analyzes the pavement profile while progressing along the pavement. This eliminates the need for a paper trace and subsequent determination of a PRI. The machines are, however, expensive and not compatible with the current mechanical profilographs owned by ALDOT. Electronic scanning alternatives analyze the traces developed by existing mechanical profilographs. They operate by optically scanning the trace and use a computer program to produce the PRI.

PROBLEM STATEMENT

In 1989, ALDOT added a policy to their smoothness specification that enables payments made to a paving contractor to be based on the level of smoothness. Contractors can receive a 5 percent bonus for above average smoothness readings or a

5 percent penalty for below average PRI ratings. Alabama is among a majority of state highway agencies that currently offers an incentive/disincentive policy, a practice which is encouraged by American Association of State Highway and Transportation officials. However, an analysis by ALDOT indicates that over three-quarters of all the 0.1 mile segments tested since the implementation of the specification have fallen in the 5 percent bonus range (Figure 1.1) without an improvement in pavement ride quality. ALDOT officials believe that some inferior pavement sections have received bonus payments due to the use of such a large payment increment (5 percent) that results in a skewed payment distribution.

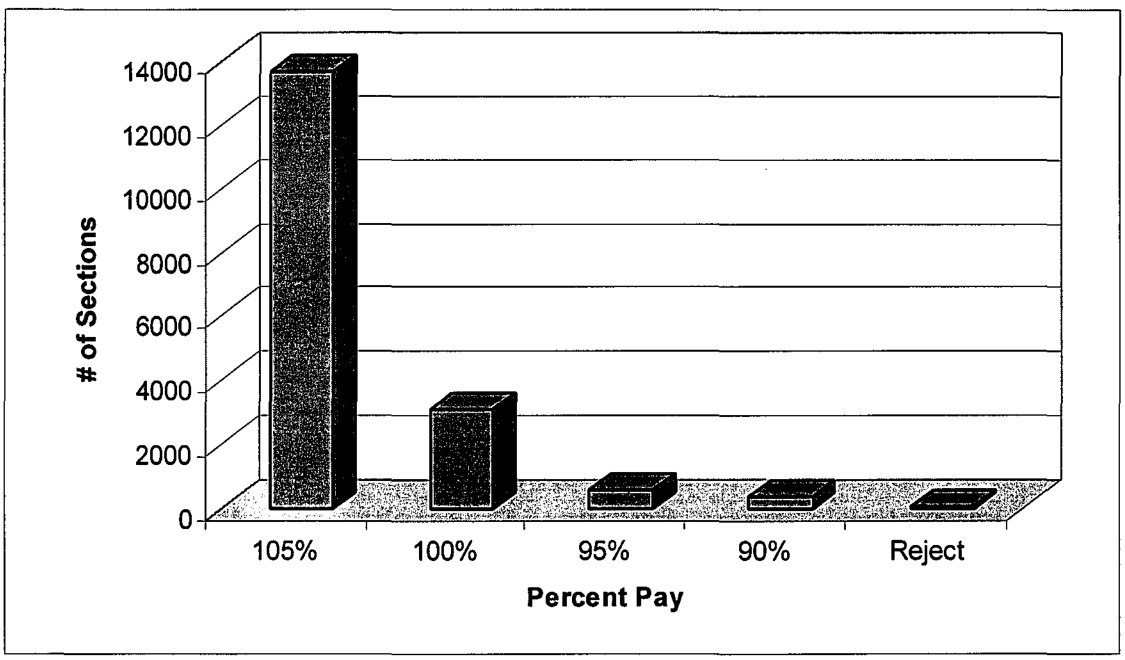


Figure 1.1 - ALDOT Pay Adjustment Distribution, 1989-1995

Other studies indicate that a thick blanking band tolerance zone, in the manual method of trace analysis, allows minor defects in the pavement to go unnoticed.

Alabama as well as most states that use the manual method for trace analysis specifies a blanking band width of 0.2 inches. In 1990, The Kansas Department of Transportation (KDOT) began studying the effect that the 0.2 inch blanking band has on the analysis results. They noticed a series of low amplitude waves in the profile of some pavements that are not being incorporated in the smoothness analysis. These low amplitude waves can dramatically affect ride quality but are not measured because they fall inside the blanking band tolerance zone. KDOT has since changed their specifications to use a zero "null" blanking band width that eliminates the tolerance limit.

OBJECTIVES

There are two major objectives of this project. The first is an analysis of an electronic scanning device called ProScan as a feasible alternative to the manual method of trace analysis. This requires determining the repeatability of ProScan to insure that the results are consistent. The second objective is to revise ALDOT's current smoothness pay scale such that it produces a more even distribution of payments. This will be accomplished by using profile trace data from recent ALDOT projects as a model for determining above average, average, and below average smoothness ratings in Alabama.

RESEARCH PLAN

This research study was performed for the Alabama Department of Transportation (ALDOT) in conjunction with the Alabama Highway Research Center. The scope of the research work was implemented as follows:

- Obtain available profilograph trace data, manual calculations, and percent payment calculations from recent ALDOT paving projects.

- Acquire a ProScan scanner device and accompanying software.
- Analyze the project trace data using ProScan at 0.0, 0.1, 0.2 inch blanking band widths to obtain the Pavement Roughness Index (PRI) for each project segment.
- Repeat the ProScan analysis 5 times for each blanking band width to characterize the repeatability of the ProScan method.
- Compare mean PRI results from the ProScan analyses (0.2 inch band width) with the manual method results to determine differences in the methods.
- Formulate modified pay adjustment scenarios using the PRI results from the ProScan analyses that recognize: various blanking band widths, reduced payment step increments, and continuous pay reduction functions rather than stepwise increments.

CHAPTER 2. LITERATURE REVIEW

During a 1960 study on the evaluation of ride quality, W.N. Carey and P.E. Irick introduced the serviceability-performance concept" as a measure of ride quality. Carey and Irick instituted a system of rating panels that would numerically rate different pavement sections based on the perceived quality of ride that each provided. The rating panels consisted of pavement specialists who gave a rating between 0 and 5 for each section, based on their perception of ride quality. The results of each panelist were combined and used to calculate a Present Serviceability Index (PSI) for each section. The sections that were assigned a PSI rating between 4 and 5 were considered to have a superior ride quality, sections rating between 2 and 4 were of average ride quality, and the sections falling in the 0 to 2 PSI range were considered poor pavements. The categorized test sections were analyzed to determine which pavement factors influenced ride quality. It was determined that 95% of a pavement's ride quality is due to the smoothness of the surface profile. Even though other factors such as vehicle dynamics and human response can influence ride quality, they do not affect the perceived ride quality as much as pavement smoothness.

Pavement smoothness is a measure of the distortions of the pavement profile from a level plane. When evaluating smoothness for newly constructed pavements or overlays the focus lies entirely on the construction process. Any irregularities in construction, such as a lack of uniformity in the thickness of the pavement layers, or poor construction can result in smoothness distortions . When evaluating pavement smoothness on pavements that have been in service the emphasis is not on the quality of their construction, but on other factors as well. Pavement distresses such as cracking and rutting, that are functions of repeated loads, will contribute to the level of smoothness. These distresses can be a reflection of a poorly constructed pavement, but in most cases are due to the quality of material used to construct the roadway. The environment also plays a key role in the performance of a pavement over time. Deterioration of one or more pavement layers due to shrinking and swelling of the subgrade in conjunction with repeated load applications can create pavement distresses that lead to smoothness variations .

In 1982, the World Bank instituted a study in Brazil called the International Road Roughness Index (IRI) to develop a standard that can be used to evaluate smoothness. The IRI is based on mathematically simulating the response of one tire on a car traveling at 50 mph. This quarter-car model (Figure 2.1) is represented by standardized parameter values of a sprung mass, unsprung mass, suspension spring rate, and suspension linear damping.

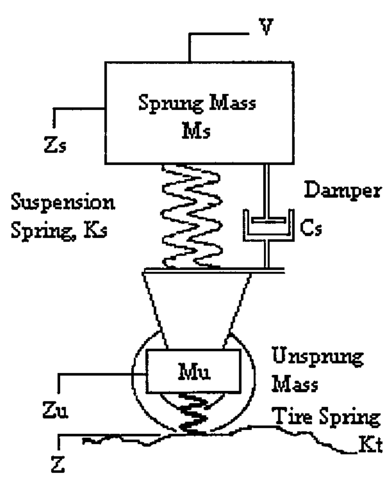


Figure 2.1 - Quarter-car Model

The IRI is based on the relative displacement of the sprung and unsprung masses at a 50 mph test speed over the length of the test section and is reported as inches of roughness per mile (in/mi). The initial study included a variety of common smoothness measuring devices for correlating to the IRI scale . Today, IRI remains the only common standard of quantifying pavement smoothness.

MEASURING SMOOTHNESS

Profiling Equipment

Profiling equipment measures and generates a profile trace of the pavement. The first profilographs, called longitudinal profilographs, were hand propelled and consisted of a rigid beam or frame mounted on a multiple-wheel support system. The profilograph measures the profile of the roadway by recording the vertical movement of a "profile wheel" attached to the frame. An analog trace, called a profilogram, can be analyzed either manually or electronically to evaluate smoothness, and some newer models are linked directly with computers . The result is a Pavement Roughness Index (PRI) that is reported as inches of roughness per mile (in/mi). More recently, however, companies have begun to produce and sell profiling systems that "read" the surface with the use of one or more lasers, instead of the profile wheel. These newer profilographs are generally broken into two groups: highspeed or lightweight.

Low-speed, Traditional Profilographs

The California Department of Transportation developed the first profilograph in the 1940's. Many variations exist, with lengths ranging from seven to twenty-five feet and four to twelve supporting wheels - in addition to the "profile wheel". These traditional models are walk-behind profilographs and are operated at low speeds (5 miles per hour or less). The McCracken profilograph (figure 2.2) is a traditional California-style model with the frame measuring twenty-five feet in length and is mounted on twelve wheels (six on each end) with the “profile wheel” located at the midpoint of the frame.

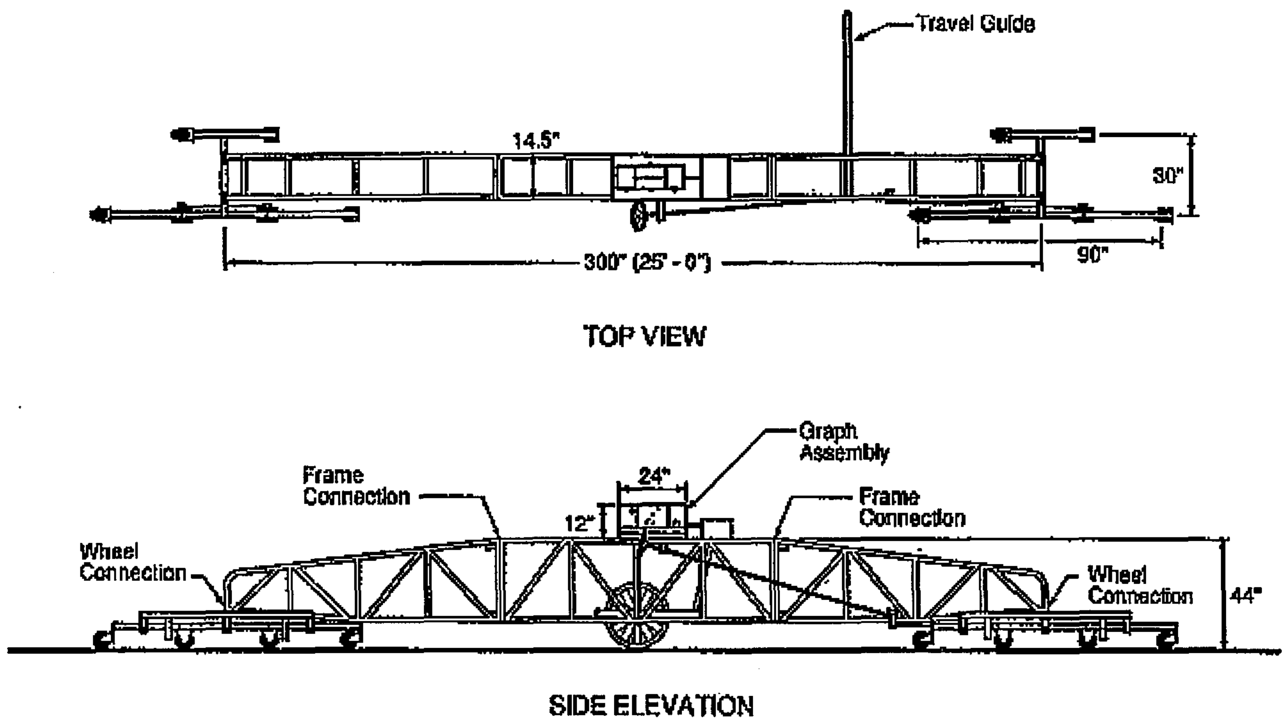


Figure 2.2 - Schematic of McCracken (California-type) Mechanical Profilograph

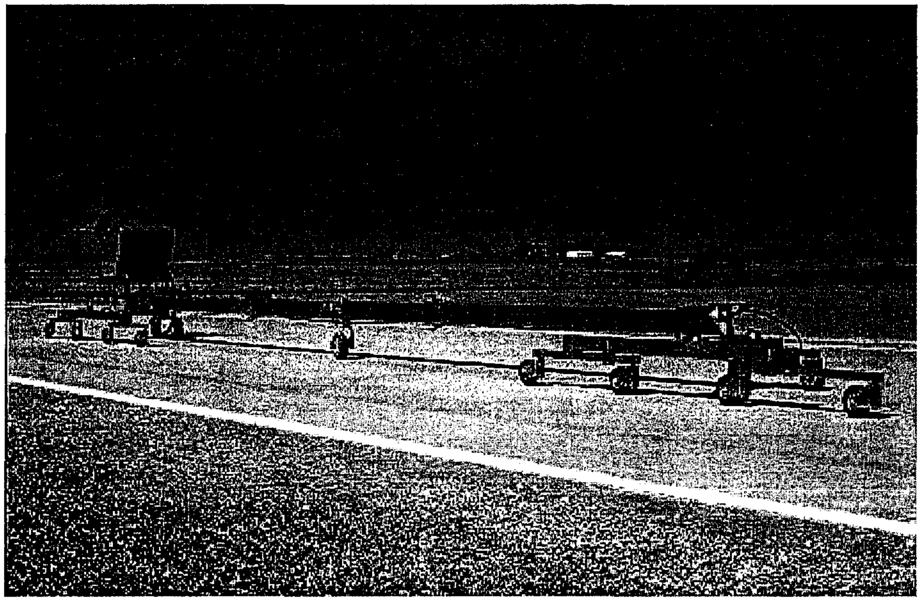


Figure 2.3 - Ames Model 4000 Profilograph

The Ames model (figure 2.3), like the McCracken, is also twenty-five feet long and mounted on twelve wheels, but consists of a rigid beam instead of a truss frame acting as the datum for the profile wheel. Both of these models are purely mechanical and produce an analog trace with a true vertical scale and horizontal scale of 1 inch = 25 feet that must be reduced manually to determine smoothness.

Paveset offers more advanced models based on the traditional California-style models. The ES2000 (figure 2.4) is one such model and is capable of reading two wheel paths simultaneously. The ES2000 is a trailer mounted system (instead of walk-behind) that utilizes mounted sensor beams to record the profile data. It requires only one person to set up and operate, as the driver of the vehicle is also the profilograph operator. A computer terminal located in the passenger seat of the towing vehicle is used in conjunction with the profilograph.

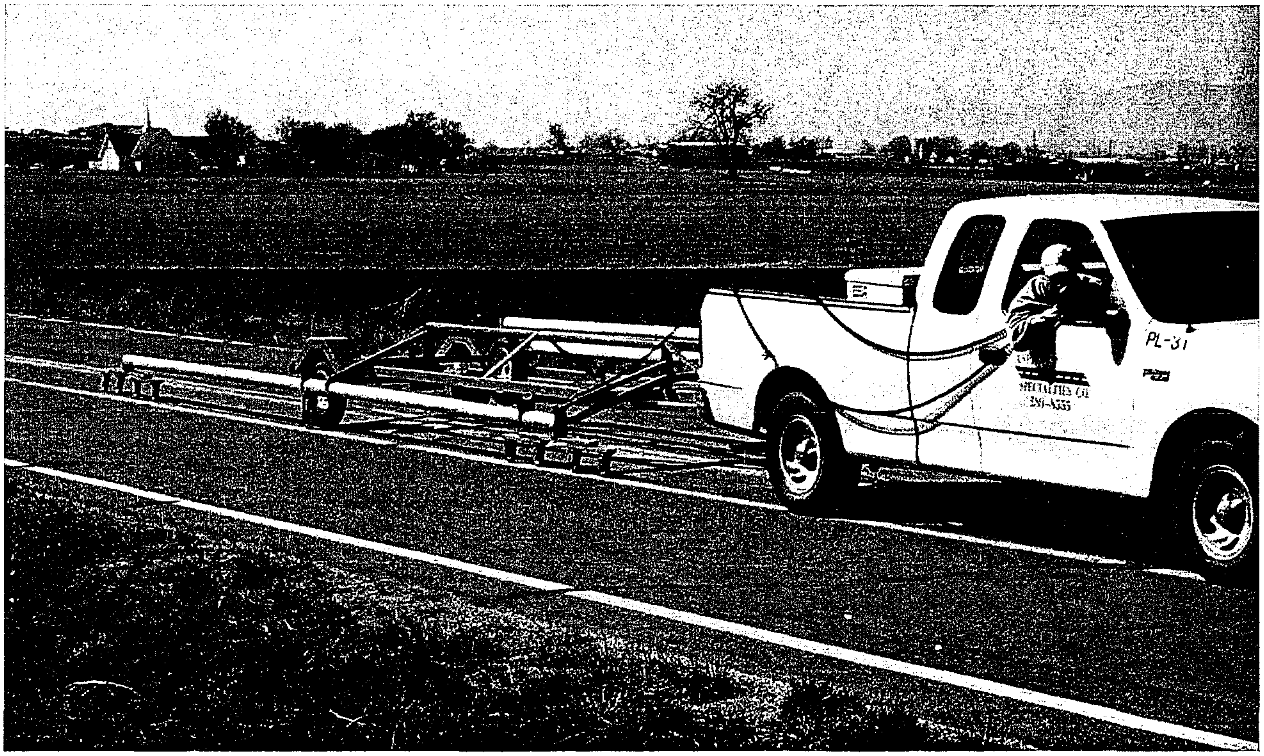


Figure 2.4 - Paveset model ES2000

Another alternative to the traditional California style profilographs is the Dipstick (Digital Incremental Profiler) produced by the Face Company. The operator of the Dipstick Profiler (figure 2.5) "walks" the Dipstick along the pavement, alternately pivoting the instrument about each leg. Two digital displays show the elevation difference between the Dipstick's two support legs, and at the end of the survey line the elevation profile and IRI are calculated and displayed.

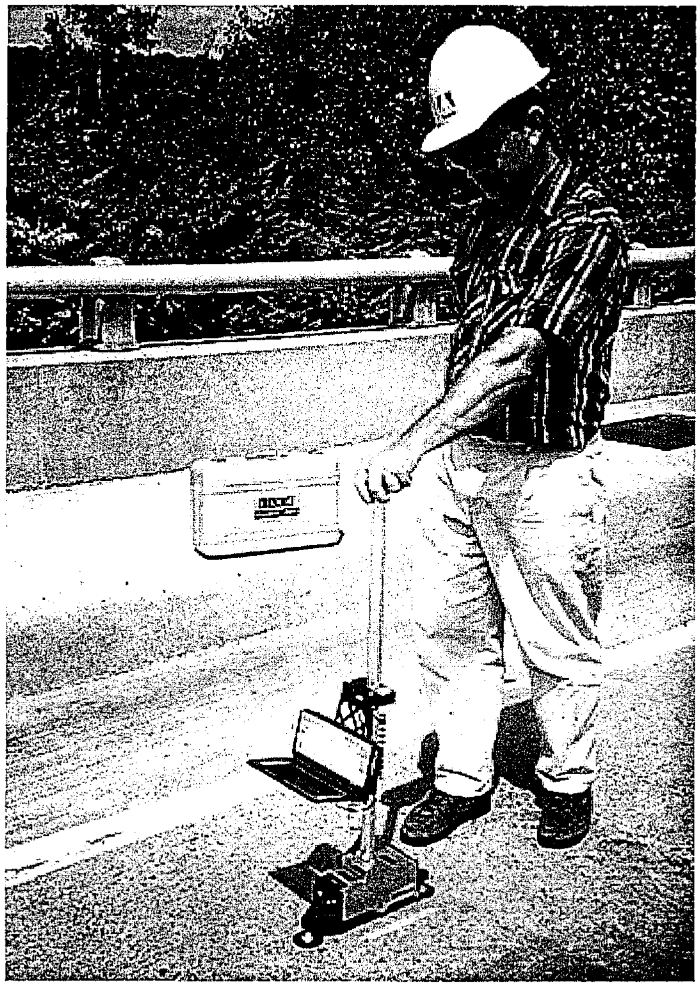


Figure 2.5 - Face Technologies Rolling Dipstick

High Speed Profilographs

These profilograph systems attach to standard pick-up trucks or other industry standard vehicles and are generally bumper-mounted. Vertical measurements of the roadway are taken by a non-contact laser sensor. Dual wheel-path measurements can be taken by making a second pass over the roadway or by adding an additional laser to the system. With the truck mounted system, profile measurements can be taken at up to 65 miles per hour. This enables contractors, etc. to profile sections of road without blocking or delaying traffic.

Surface Systems and Instruments (SSI) is one such manufacturer of high-speed profiling equipment. Their system (figure 2.6) uses a software package known as ProTrac and a lap-top computer with printer for output. The high speed profilograph enables profiles to be taken much quicker, but have a much higher cost. SSI's basic high speed system starts at $41,000 for a single laser system and does not include the truck or van to be used.

Figure 2.6 - SSI High Speed Profiler System

K.J. Law offers two high speed profilographs, the T6500 and T6600. Both models operate in the same manner as SSI's model, but both K.J. Law packages include the computer and the van - which drives the cost up to $175,000. These profilers can be used at speeds up to 70 miles per hour with the on board computer system storing pavement profiles, rut depths, and roughness indexes.

Computer Specifications:

- IBM compatible
- 80486 Processor with integral Math co-processor
- Flat Screen monitor
- Dual 5-1/4" or 3-1/2" floppy disk drive
- Solid state disk, 20

Performance Standards:

Acceleration Resolution:	1 micro g
Infrared Sensor Resolution:	0.025 mm (.001 inch) static,
	.25 mm (.010 inch) dynamic
	6mm x 37 mm (.24 in x 1.46 in) surface spot area
Profile Sampling Rate:	25 mm (1 inch)
Profile Repeatability:	Precision : 0.5 mm (.02 inch)

Figure 2.7 - K.J. Law Models T6500 and T6600

Lightweight Profilographs

Lightweight profilers are designed to be used mainly for new pavements and during construction of the roadway. Because of the weight, they can be used on freshly laid asphalt or concrete. The idea behind the lightweight profilers is to give the contractor an opportunity to evaluate the smoothness of the roadway and correct any problems before pavement has fully hardened or before the construction crew and equipment are taken off the site. These profiling systems operate in the same manner as their highspeed counterparts, employing the use of laser sensors to measure the wheel paths. The sensors are usually attached to some form of golf cart or other utility vehicle and require a trailer for transportation to the site. Generally, they operate at speeds around 10-25 miles per hour. Lightweight systems offer the same options as the highspeed profilers, except for the speeds, at a substantially lower price (around $30,000). Most of the companies that produce highspeed profiling equipment, K.J. Law, SSI, and Ames(figure2.9), offer lightweight systems as well.

SSI's lightweight laser profiler (figure 2.8) is a utility vehicle capable of capturing profiles of newly constructed roads at speeds up to 25 miles per hour. The vertical measurements of the surface are taken by a non-contact laser designed to read a variety of roadway textures and colors. SSI claims resolution is better than 0.1mm (0.005 in). This model is capable of dual wheel-path testing and reporting. After the first pass over than section, operators can reverse the utility vehicles direction and collect data for the adjacent wheel paths. These multiple traces can be reported on a single report. A special feature of SSI's model is the ability to append new readings to previous data readings, enabling contractors to compare the original conditions with the newly constructed roadway. The system includes an on-board printer and lap-top computer with “ProTrac” profilograph software and “ProScan” scanning system.

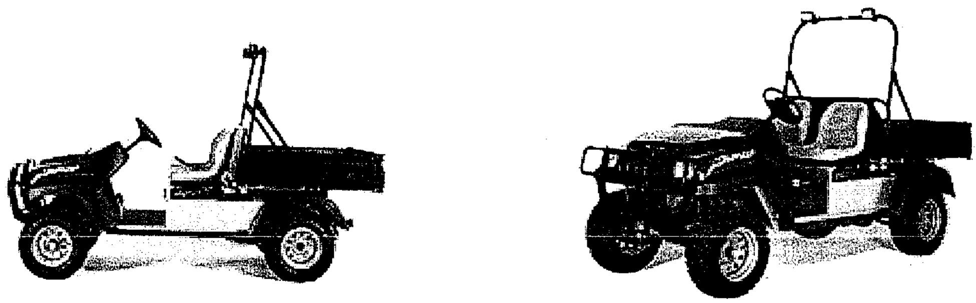


Figure 2.8 - SSI Lightweight laser profiler

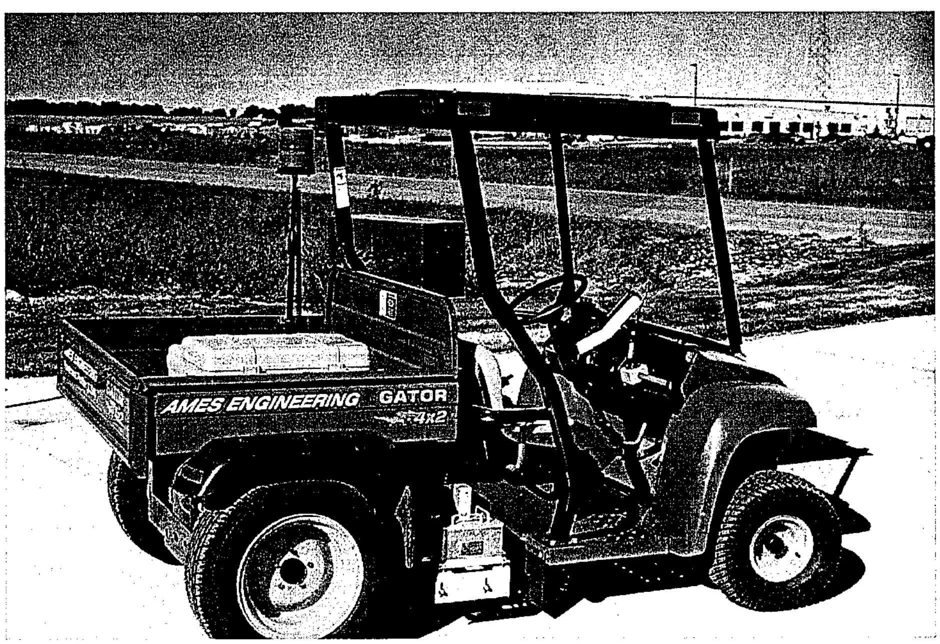


Figure 2.9 - Ames Model 6000 L.I.S.A. Profiler

Response-type Road Roughness Measuring Systems

Response-type road roughness measuring systems (RTRRMS) evaluate smoothness with a mechanical device that measures the dynamic response of the rear axle with respect to the vehicle frame . The Mays Ride Meter (Figure 2.10) is an RTRRMS that attaches to the rear axle of an automobile or trailer. When driven over the pavement at a specified speed it measures the vertical movement of the axle with respect to the vehicle frame. A major problem with RTRRMS devices is that their measurement is dependant upon the characteristics of the host vehicle/trailer and the speed at which the measurements are taken . Various vehicle components such as suspension characteristics, tire pressure inconsistencies, and vehicle weight changes can have an effect on the test results. Furthermore, to attain reasonably accurate and reproducible results, it is important to regularly perform difficult and expensive calibration procedures .

CHAPTER 3. PROFILOGRAM REDUCTION METHODS AND PROCEDURES

MANUAL METHOD

The manual method of reducing the trace produced by a mechanical profilograph involves using a special plastic scale that is approximately 1.7 inches wide and 21.12 inches long (figure 3.1). One length of the plastic template represents a 0.1 mile segment of the profile trace at the 1 in. = 25 ft. scale of the trace so that 5280 ft * (in/25 ft) = 21.12 in. At the center of the template is a solid color band, that can vary in width from 0.0 to 0.2 inches. The purpose of the solid color band is to "blank out" or cover up a portion of the trace. A step by step use of the profile scale follows.

(A) jagged peaks are smoothed with a fine-point pen. Smoothing is necessary because the surface texture of the road can cause small spikes to appear along the trace.

(B) place the blanking band template over the trace and position it to cover up as much of the trace as possible. Vertical deviations or "scallops" above and below the positioned blanking band are counted and recorded using the scribed lines on the template. Each scribed line or unit on the template represents 0.1 inch.

(C) scallops are measured to the nearest 0.05 inches or half unit on the scale unless the scallop is less than 0.08 inch in width. In the example shown below the scallop is considered a spike (Figure 3.1) and is not counted.

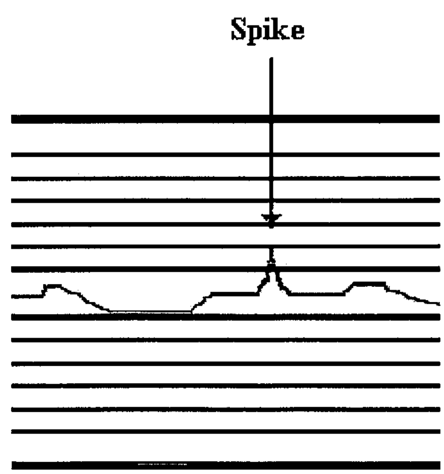
(D) by centering the blanking band over the trace, the scallops above the blanking band are usually in balance with the scallops that appear below the blanking band. In some cases, such as superelevation of the roadway, the general profile of the trace may shift causing difficulty in centering the blanking band on the trace. When this occurs, the position of the blanking band can be altered in order to cover a small section of the trace at a time.

(E) when the scallop measurements are summed and divided by the test section length of 0.1 mile to obtain a pavement roughness index (PRI) with the units of inches per mile (in/mile). For the case in Figure 3.2, adding the scallop heights for the segment produces a measured roughness value of 0.55 inches. Dividing this value by the segment length of 0.1 mile generates a PRI of 5.5 $^{in}/_{mile}$ (Example 3.1). After the PRI is determined for a test section the blanking band template is moved to the next 0.1 mile section of the trace and the process is repeated.

Example 3.1 - Calculation of PRI

Segment Length = 528 feet =
Measured Roughness = 0.55 inches
PRI = $^{0.55\ in}/_{0.1\ mile}$ = 5.5 $^{in}/_{mile}$

Figure 3.1 - Spike



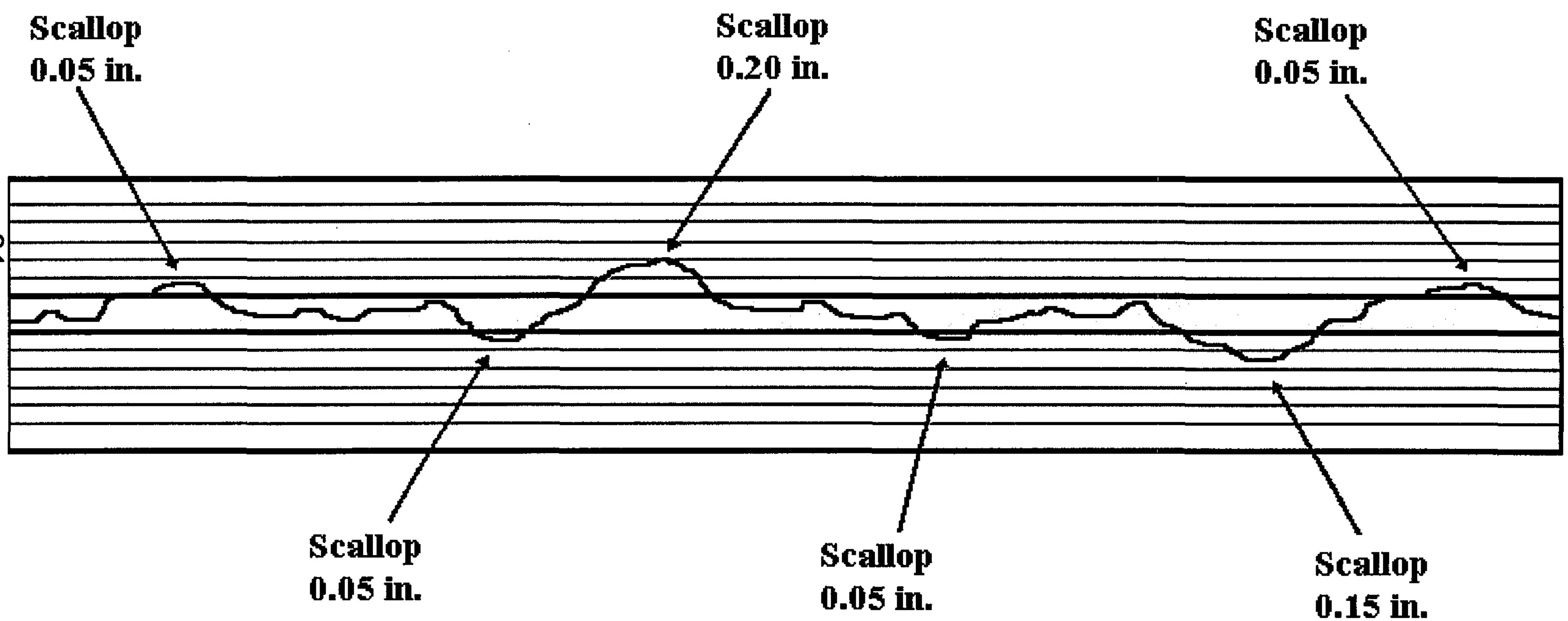


Figure 3.2 - Measurement of PRI using Manual Method

Some state highway agencies also require locating bumps on the profile trace. Bumps are deviations that exceed 0.3 inches in height and require corrective action such as grinding or milling by the contractor. Bumps are identified on the trace with a clear, plastic template that is approximately 3 inches wide and 5 inches long. On the front of the bump template is a horizontal line that is 1 inch long and terminated by two short vertical lines that are $^{1}/_{8}$ inch. A 1 inch slit in the template is located 0.3 inches above and parallel to the scribed line and is just wide enough to fit the tip of a pencil. The template is placed on the profilogram so to align the scribed line under the base of a bump. A line is drawn through the slit in the template onto the trace to note the area of the bump that exceeds 0.3 inches in height. The template is then moved to the next bump and the procedure is repeated .

PROSCAN AUTOMATED PROFILOGRAM REDUCTION SYSTEM

An alternative method of reducing the trace produced by a mechanical profilograph is with the use of an automated profilogram reduction system. ProScan is a DOS based system developed by Devore Systems, Inc. that consists of a hand scanner mounted on a paper transport unit. The transport unit scrolls the trace paper produced by the McCraken and Ames mechanical profilographs at a continuous rate while the scanner captures the trace information. The trace is digitized by an image enhancement program and stored on a disk. A two-sided moving-average filter is applied to the recorded profile. The purpose of the filter is to remove the sharp deviations caused from pavement texture or profilograph vibration; similar to using a fine-point pen in the manual method of trace analysis. The ProScan software performs a least-square error analysis to determine the best fit linear line and measures scallop heights to determine the PRI. It can also indicate the location of bumps that occur on the profile trace. The results can be displayed on screen or can be printed in report format. ProScan also offers the ability to change the reduction parameters at which the profile trace is analyzed. The operator has the ability to define certain criteria such as blanking band width, segment length, filter length, scallop resolution, minimum scallop height, minimum scallop width, and minimum bump height as required in the specifications. A big advantage of ProScan is the relative ease and speed that a profilogram trace can be analyzed compared to the manual reduction procedure. The ProScan system currently costs about $6000 and requires a 486SX33 computer or better to run the program.

ProScan Operation

Prior to any ProScan analysis a perpendicular line is drawn on the trace to establish the start of the first segment. The line needs to be at least a sixteenth of an inch thick and should be drawn such that it is bisected by the profile trace. The trace needs to be marked in the same manner at the very end of the trace for ProScan to identify the end point. The Ames and McCracken profilographs produce profile traces on two different types of paper. The Ames paper is standard 8 ½ by 11 inch computer paper with perforated tractor feed strips on the sides and the McCracken paper is a continuous roll approximately 12 inches wide. The ProScan paper transport unit uses a tractor feed for the Ames paper and a roller assembly for the McCracken paper.

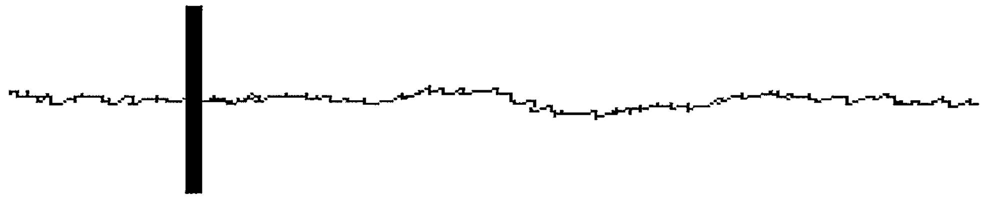


Figure 3.3 - Start/End of Scanning Indicator

The roll is placed on the dispenser bar at the front of the transport unit and the paper is fed over the top of the unit such that the end of the paper hangs off the back of the unit. The scanner is mounted flat on the paper and centered over the trace.

The DOS-based ProScan program provides on-screen instructions and prompts for a filename, paper orientation (up station/down station), beginning station location and optional data such as paving dates, project numbers, project location, lane direction, and type of construction. As the trace is being scanned the computer monitor displays the profilogram trace and a thin line that represents the center of the trace. The operator monitors the scanning process to insure that the trace line and the thin centerline are parallel. This indicates that the program is recognizing and reading the proper trace line instead of stray marks that may appear on the profilogram paper. When the scanner reaches the first line across the trace (start line) the unit will beep in recognition of the start of a segment. The scanning will automatically stop and pause for a few seconds at the end of each segment while the information is transcribed to two files. The first file is a spectral density file (.psd) that contains the digitized trace information. The second is a report file (.psa) that contains the PRI results from the trace reduction analysis. This process continues for each segment until the scanner reaches the end line which was placed across the trace. The computer monitor will display the analysis results of each segment and enable a report of the results, a copy of a segment, program termination, or continue scanning.

The analysis of the PRI is based on the criteria specified in the configuration file (PROSCAN.CFG). Figure 3.3 represents the configuration file for ALDOT's current reduction criteria. The proper values of blanking band width, minimum scallop height, minimum scallop width, scallop resolution, filter length and units of measurement must be specified to insure that the correct method of analysis is achieved. A previously saved trace can be analyzed again using a different set of reduction criteria by creating a new configuration file. For example, metric units instead of English units can be used in a new analysis of a data file by using a metric configuration file.

CHAPTER 4. DATA ANALYSIS

The data used for this project consisted of profile traces from 20 ALDOT paving projects that were constructed during the period from 1991 to 1995. Table 4.1 summarizes the profilogram data provided for the project by ALDOT. The profilograms were produced using either a McCracken or Ames style profilograph. Included with the traces were calculated values of the Pavement Roughness Index for each 0.1 mile segment of the trace as determined manually by ALDOT personnel. The data consisted of 326 lane miles of data which resulted in 3310 segments of 0.1 mile or less in length. The profilogram for each segment was scanned and analyzed by ProScan five times using the same reduction criteria currently used by ALDOT for manual trace reduction. The traces were also analyzed using a variation of different reduction parameters by changing the blanking band widths to 0.1 and 0.0 inch and the scallop resolution to 0.01 inch.

The data analysis steps included the following:

- ProScan Consistency. Each of the 3310 profilograph traces was reduced five times by the scanning reduction system. The purpose of this multiple scan was to determine if the ProScan system was capable of providing consistently reliable readings. Consistency was ascertained by inspection and analysis of the population standard deviation and the ability of the ProScan system to identify bumps and scallops.

Table 4.1 - Summary of ALDOT Pavement Smoothness Data

Division	Project Number	Project Designer	Date	Lanes	Type	Length (lane miles)	# of Test Segments
1	IM-65-3(132)	1A	Aug-93	4		19.07	192
	STPAA-398(39)	1B	Aug-95	4		14.25	144
2	NHF-398(40)	2A	Oct-93	2	Overlay	8.39	85
	D-2113(1)	2B	Nov-93	2		11.77	118
	APD-471(29)	2C	Oct-94	4	New Construction	22.17	223
3	IR-59-1(172)105	3A	Jun-91	8		26.93	271
	IR-459-4(64)24	3B	Jun-91	6		22.78	228
	99-303-644-069-301	3D	Oct-93	2		9.73	99
	STPAA-6407-107	3E	Jul-95	2	New Construction	13.94	142
4	IM-85-1(116)	4A	Apr-94	4	Overlay	15.94	160
	DBAAF-9062(2)/ MAAA-9062(3)	4B	Jul-95	2	New Construction	2.95	30
5	99-305-543-006-401	5A	Jun-94	2	Overlay	10.75	109
6	IM-85-1(111)	6A	Jan-93	4		22.22	238
7	NFH-449(8)	7A	Mar-95	4		21.52	220
	99-307-234-053-502	7B	May-95	4		23.39	237
	IA-003-000-002	7D	Sep-95	2		1.40	14
8	IM-59-1(175)	8A	Aug-92	4	Overlay	16.04	161
	IM-59-1(179)	8C	May-93	4	Overlay	4.62	48
9	IM-65-1(206)	9A	Nov-94	4	New Construction	47.16	480
	DE-0019(802)	9B	Sep-95	4	Overlay	10.92	111

- Comparison of Manual and ProScan Readings. A comparison of the manual and ProScan methods was performed after reliability of the ProScan system had been established. This comparison was performed to determine if ProScan could acceptably simulate the manual method of data reduction. The analysis is not as straight forward as may first appear. For example, the original profilograms that were used to obtain the manual readings were also used for obtaining the five ProScan readings. Since the ProScan system was applied five times and consistent results were obtained there is a high degree of confidence in the result. The same is not true for the manual readings. Only one manual reading for each analysis segment, was obtained by unknown individuals in uncontrolled environments.

- Determination of Pay Adjustment Factors. After the feasibility of using ProScan for smoothness measurement had been established, the data was used as a model for developing new pay adjustment factors. Alabama has been predominantly paying 5% bonuses on pavement segments constructed since the adoption of the incentive/disincentive policy in 1989. The incentive payments, are intended to motivate contractors to achieve smoothness levels above the minimum requirement. However, when the incentive payment threshold is at a level that can be reached repeatedly, the motivation for improving quality does not exist. By using the database as a sample of the overall pavement smoothness levels in Alabama, new pay adjustment factor levels can be created to produce a more even distribution of payments.

PROSCAN CONSISTENCY

The data set consists of profilograms of 3310 roadway segments 1/10 of a mile or less in length. The 1/10 mile segments are the result of ALDOT standard procedures with the shorter lengths resulting from total project lengths not equaling 1/10 of a mile multiples. The data was obtained from 20 projects performed in nine ALDOT Divisions by various contractors. Each project was completed by different road crews, using different equipment and asphalt mix on different terrain and subbase conditions. The profilograph traces between projects is, therefore, both independent and mutually exclusive. The same consideration can be applied to each 1/10 mile segment within each project. While it is expected that the contractor, and possibly the equipment remains the same, variations in the sublease and surface preparations, asphalt mix, and equipment operations and performance can result in different smoothness readings between segments. The smoothness readings between each segment are, therefore independent and mutually exclusive.

The profilograms of each project were accompanied by a manually derived profile roughness index (PRI). These PRI's were developed by ALDOT personnel using a 0.2 inch blanking band at a resolution of 0.05 inch and were used to evaluate pavement smoothness. No additional manual readings were obtained since the variability of manual PRI reductions was determined from prior studies. These studies indicate that the variability in the manual PRI's for each segment, as measured by the standard deviation varied from 0.7 to 4.8 in/mi, with an average standard deviation of 2.9 in/mi.

The five ProScan runs were performed to enable an assessment of the repeatability of the system. The analysis was performed, by project, on the standard deviation of the repeat measurements for each segment. Table 4.2 summarizes the distribution of the standard deviation for the entire ProScan data base using a 0.2 inch blanking band at a resolution of 0.05 inch (205). ProScan is capable of reducing the data at a number of different blanking bands and resolutions but the 205 data was obtained to match the blanking band and resolution used for manual data extraction in Alabama. The range of the ProScan standard deviation is from a minimum of 0 (2596 observations) to a maximum of 0.38 (1 observation) with 90% of all observations less than a standard deviation of 0.20.

Table 4.2 - Summary of ProScan Standard Deviation for Entire Data Base (0.2 in. Blanking Band with 0.05 in. Resolution)

	Percentile			Range	
	50	90	95	Minimum	Maximum
Standard Deviation (in/mi)	0.0	0.2	0.24	0.0	0.38

Table 4.3 summarizes the range and average standard deviation of the ProScan readings for each project. The variability exhibited in Table 4.2 ranges from a minimum of zero to a maximum of 0.38 in/mi. The largest average standard deviation was 0.120 in/mi. These results are considerably lower than the range of 0.7 to 4.8 in/mi, and average of 2.9 in/mi, obtained for the variability of manual observations from other studies. These comparisons indicate that the ProScan system will provide more consistent results than the manual ratings. Reducing variability has the advantages of:

- Reducing the influence of the ability, experience and subjectivity of the individual performing the profilogram reduction.
- Helps ensure a uniform reduction of profilogram data within and between divisions.
- Reduce possible contractor complaints pertaining to the perceived experience and inherent accuracy of the individual performing the profilogram reduction.

Table 4.3 - Analysis of ProScan Consistency by Project (0.2 in. Blanking Band with 0.05 in. Resolution)

		Parameters of Five ProScan Readings Parameters		
		Range		
Project ID	Number of	Minimum	Maximum	Mean
1A	192	0	0.28	0.039
1B	144	0	0.37	0.067
2A	85	0	0.24	0.033
2B	118	0	0.37	0.094
2C	223	0	0.38	0.071
3A	271	0	0.28	0.024
3B	228	0	0.20	0.005
3D	99	0	0.37	0.117
3E	142	0	0.37	0.052
4A	160	0	0.37	0.034
4B	30	0	0.37	0.076
5A	109	0	0.37	0.091
6A	238	0	0.37	0.077
7A	220	0	0.37	0.050
7B	237	0	0.37	0.044
7D	14	0	0.24	0.120
8A	161	0	0.24	0.026
8C	48	0	0.24	0.027
9A	480	0	0.37	0.015
9B	111	0	0.37	0.097

Five readings of the ProScan system were obtained for this study to enable the evaluation of system consistency. Actual applications of the ProScan system, however, will consist of obtaining only one reading. Determining which of the five readings to use for further analysis in this project yields four alternatives. These alternatives are using a representative reading such as the mean, median, mode or the random selection of one reading.

The mean was chosen as the evaluation variable since it provides the best estimate of the expected long term outcome. In addition, comparisons between the mean, median and mode revealed that there is little difference between them. This small difference is evident when considering the small standard deviation that existed in the ProScan readings.

COMPARISON OF MANUAL AND PROSCAN READINGS

Since only one measure of ProScan will be obtained it is necessary to determine the type of association between the ProScan and the manual methods. This is necessary since adopting the ProScan system could result in a completely different set of smoothness measurements. If the ProScan measurements are not the same as those obtained in the past then a difference in the incentive payments made to the Contractor will result; necessitating a new pay adjustment scale. The association between ProScan and manual methods was performed by considering the following:

- Linear Association - The ProScan and manual methods should exhibit a linear association if the methods are equivalent. For example, consider a hypothetical case where the manual method exhibits uniform fluctuations, and the ProScan method quadratic fluctuations, in their smoothness measures. Such a difference in data distribution would result in drastic differences in manual and PRI readings for different data reduction conditions.

- Similar Trends - The ProScan and manual methods should exhibit similar trends if the methods are equivalent. If the manual method indicates that a segment has a lower rank than an adjacent segment then the ProScan measures should exhibit the same trend. Measures of smoothness should not be subjective. The measured value between segments may change in magnitude but the relative ranking between segments should be consistent regardless of the method of measure.
- Categorical Equality - The level of approval for pavement smoothness is based on acceptance categories. PRI values falling between specified intervals result in different incentive payments. If the manual and ProScan methods result in different categorical equivalents then it will be necessary to determine different incentive thresholds.

MEASURES OF ASSOCIATION DEFINED

A graphical and statistical comparison of the ProScan and manual PRI's was conducted to determine if ProScan provides similar results as the manual method for a wide range of data reduction condition. The graphical analysis consists of scatter plots of the manual versus ProScan smoothness readings for each project. These scatter plots were developed to provide a visual clue of any association between the manual and ProScan readings. They reveal a linear relationship between the manual and ProScan methods since the observations are clustered around a straight line. Constructing a 95 percent confidence interval around this line indicates the majority of observations are within ± 2.5 % of the average.

Notice that numbers are annotated at the observation points that are outside of the 95 percent confidence interval. These are the case numbers of the data observation and were investigated to determine their source. In all cases they were due to manual observations and appear to be outlines. With this in mind, the original idea aw to remove them from the analysis. Upon further consideration it was determined that the manual readings were the actual readings that were used to determine the contractor incentive payout. Removing the outlyers resulted in a smaller confidence band and the migration of other manual readings to the peripheral of ht band extent. The outlyers of the manual readings were retained in the analyses.

Regression modeling was performed to determine if the ProScan readings were a dependable predictor of the manual data. The scatter plots indicated that a straight, linear, line provided the best fit. A linear regression was performed therefore, with the manual readings modeled as the dependent and the mean ProScan readings as the independent variables.

Table 4.4 presents the regression parameters, and summarizes the statistical measures, of linear association between the manual and average ProScan ratings. The intercept and slope result from a linear regression model between the manual and average ProScan ratings for all of the segments within each of the 20 projects. The intercept is the expected value of the manual rating when the average ProScan rating is equal to zero. The slope is the expected change in the manual rating when the ProScan rating changes by one unit. An exact linear relationship has an intercept of 0 and a slope of 1.

For linear regression the intercept and slope provide the parameters to write the equation of the straight line as the statistical model. For example the estimated model for project 1A is:

manual reading = 0.16 + 0.31 (mean ProScan)

The simple correlation between manual and the mean ProScan readings is provided by the R^2 statistic. The R^2 is often interpreted as the proportion of the total variation in the manual readings accounted for by the mean ProScan readings. If there is no linear relationship between the dependent and independent variable the value of R^2 is 0 or very small. If all of the observations fall on the regression line, R^2 is 1.

Table 4.4 - Measures of Association Between Manual and ProScan Smoothness Readings

LINEAR ASSOCIATION				K-S NORMALITY TEST		TREND TEST	
	Regression	Parameters				Spearman	
Proj	Intercept	Slope	R^2	Manual	ProScan	Correlation Coeff.	Significant
1A	0.16	0.31	0.91	no	no	0.90	yes
1B	0.14	0.92	0.91	no	no	0.93	yes
2A	0.19	0.81	0.64	no	no	0.78	yes
2B	1.03	1.00	0.84	no	no	0.91	yes
2C	1.48	1.02	0.75	no	no	0.83	yes
3A	0.33	1.11	0.80	no	no	0.79	yes
3B	0.11	1.24	0.67	no	no	0.75	yes
3D	1.06	0.78	0.67	no	no	0.73	yes
3E	1.02	0.88	0.70	no	no	0.86	yes
4A	0.79	0.93	0.53	no	no	0.70	yes
4B	1.92	0.61	0.57	no	no	0.71	yes
5A	0.29	0.91	0.89	no	no	0.93	yes
6A	0.50	1.21	0.76	no	no	0.88	yes
7A	0.67	1.01	0.82	no	no	0.84	yes
7B	0.96	1.17	0.69	no	no	0.75	yes
7D	2.48	0.76	0.67	yes	yes	0.80	yes
8A	0.53	1.09	0.55	no	no	0.71	yes
8C	0.00	1.29	0.89	no	no	0.84	yes
9A	0.47	0.95	0.67	no	no	0.59	yes
9B	0.33	0.76	0.91	no	no	0.96	yes

[1] level of significance $\alpha = 0.05$

The last measure of association between the manual and ProScan readings is the correlation coefficient. This measures is easily interpretable, does not depend upon the units of measurement, and provides an absolute measure of how well the model fits the data. Selecting the correct correlation test however, requires knowledge if the data is normally distributed. This was determined by applying the K-S test. The K-S test compares the observed cumulative distribution in these cases normal. The analysis for the manual and the mean of the ProScan index profile indexes are summarized in Table 4.4. Since the data does not exhibit a normality distribution the specimen rank order correlation test was used. If there is a negative correlation between two variables than an increase in one variable tends to result in a decrease in the other variables. Similarly a positive correlation indicates than an increase in a variable tends to cause an increase in the other.

RESULTS OF ASSOCIATION TEST

The coefficient of determination, R^2, the intercept and the slope values indicate that the ProScan readings provide good estimates of the manual readings. Not only is a good estimate received but the ProScan method is not subject to the wide variations in measurements between analysis segments exhibited by the manual readings. Table 4.4 indicates that the (K-S) normality test with the exception of Project 7D, provides no evidence of normality for either the manual or average ProScan ratings. This influences the type of statistical tests and methods that are appropriate for the smoothness data. For example, the absence of normality results in the need to use an ordinal measure of association between the manual and average ProScan ratings. The Spearman correlation coefficient, displayed in the last two columns of Table 4.4, indicates that there is a significant monotonic relationship between the two variables. In other words a high (low) ranking with a manual observation tends to occur jointly with a high (low) ranking of the ProScan observation. This demonstrates that high and low manual profile readings are accompanied by respective high and low mean ProScan readings.

CATEGORICAL EQUALITY

Since neither the manual or ProScan data exhibited normal distribution characteristics, a non-parametic test was used to determine if they were statistically equal. This was accomplished by considering the manual and average ProScan rankings as paired (related) observations for each segment. The results of the non-parametric Wilcoxon paired samples test is summarized in Table 4.5. The manual and average ProScan ratings were only statistically equal for projects 1B, 3D, 5A, and 8C. Not only are the manual and average ProScan ratings not statistically equal but ProScan readings yield consistently lower PRI ratings; as summarized in table 4.6. Sufficient information was not available on the characteristics of each project to determine the possible reasons for differences in the tests of statistical difference.

Table 4.5 - Summary of Wilcoxon Paired Samples Test Between Manual and ProScan

Project	Segments Analyzed	Wilcoxon z value	Statistically
1A	192	6.31	no
1B	143	0.23	yes
2A	85	2.04	no
2B	118	8.47	no
2C	223	12.05	no
3A	271	9.48	no
3B	228	5.99	no
3D	99	0.13	yes
3E	142	7.19	no
4A	160	8.93	no
4B	30	3.79	no
5A	109	1.59	yes
6A	238	9.64	no
7A	220	9.89	no
7B	237	12.21	no
7D	14	3.17	no
8A	161	7.70	no
8C	48	1.81	yes
9A	480	12.77	no
9B	111	5.73	no

[1] level of significance $\alpha = 0.05$

Table 4.6 - Summary of differences in manual and ProScan readings by segment

		ProScan < Manual		ProScan = Manual		Manual < ProScan	
Project	**Analyzed**	**No.**	**%**	**No.**	**%**	**No.**	**%**
1A	192	81	40.5	91	47.4	20	12.1
1B*	143	48	33.6	40	28.0	55	[38.4]
2A	85	24	28.2	46	54.1	15	17.7
2B	118	101	85.6	8	6.8	9	7.6
2C	223	196	87.9	19	8.5	8	3.6
3A	271	132	48.7	127	46.9	12	4.4
3B	228	51	22.4	175	76.8	2	0.8
3D*	99	46	46.5	6	6.1	47	[47.4]
3E	142	95	66.9	26	18.3	21	14.8
4A	160	121	75.6	26	16.3	13	8.1
4B	30	25	83.3	2	6.7	3	10.0
5A*	109	37	33.9	14	12.8	58	[53.3]
6A	238	153	64.3	54	22.7	31	13.0
7A	220	146	66.4	52	23.6	22	10.0
7B	237	194	81.9	37	15.6	6	2.5
7D	14	13	92.9	0	0	1	7.1
8A	161	102	63.4	44	27.3	15	9.3
8C*	48	14	29.2	26	54.2	8	16.6
9A	480	238	49.6	223	46.5	19	3.9
9B	111	17	15.3	23	20.7	71	[64.0]

[ ] Manual ranking predominantly less than ProScan ranking
* Manual and ProScan statistically equal (See Table 4.5)

CHAPTER 5. DETERMINATION OF PAY ADJUSTMENT FACTORS

Two different styles of pay adjustment factors were considered: stepwise payment increments and continuous payment functions. Alabama currently uses a step function with 5% increments. These relatively large increments between payment levels results in the potential for a large payment difference between two borderline segments. For example, consider two segments that do not vary significantly in overall rideability but fall into two different payment ranges. One may be at the low end of the 105 percent payment range with a PRI of 2.5 and the other at the high end of the 100 percent range with a PRI of 3.0. The PRI values in this case are not significantly different or at least not different enough to warrant such a large difference in payment.

One solution to this problem is to create adjustment factors with smaller steps (1 or 2 percent) so that two borderline segments do not receive payments that differ as much as they do with steps at 5 percent increment steps. Another solution is to apply a continuous linear relationship between PRI values and pay adjustment factors instead of using a step function pay scale. This alternative assigns pay factors that are strictly a function of the PRI value instead of creating pay factor ranges that allow for a range of PRI values to achieve the same bonus or deduction. Figure 5.1 shows a graphical representation of the relationship between Pay Factor and PRI for this alternative. The problem with this method is that there is only one PRI value that will yield a pay factor of 100 percent. This means that there is no specified acceptance range. Almost all pavement segments on a project will receive either some type of bonus or deduction leaving it impossible for contractors to bid on a project when they know that actual payment will be different. Therefore, this method will not be considered when producing new pay adjustment scales.

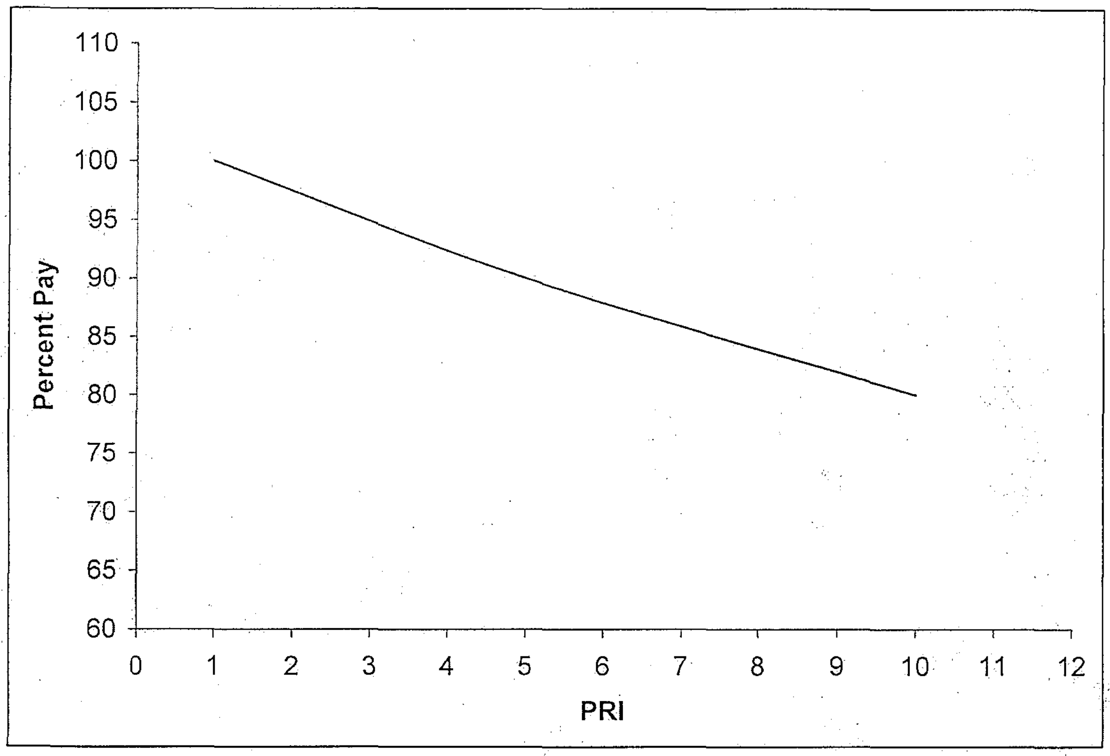


Figure 5.1 - Continuous Function Relationship Between Pay Factor and PRI

A third alternative is to combine the step function relationship with the continuous function concept by specifying a 100 percent acceptance range with linear relationships in the bonus and penalty ranges. Figure 5.2 shows a graphical relationship of this method. This allows for bonuses and penalties to be a function of the PRI achieved while still specifying an acceptance range. The advantage of this method is that a pavement section that has a PRI value that falls just outside the 100 percent acceptance range receives only a minor bonus or penalty instead of a large bonus or penalty that it would receive with a step function pay scale. At the same time there is an acceptance region that gives contractors a tolerance range that they can expect to receive full pay for their work.

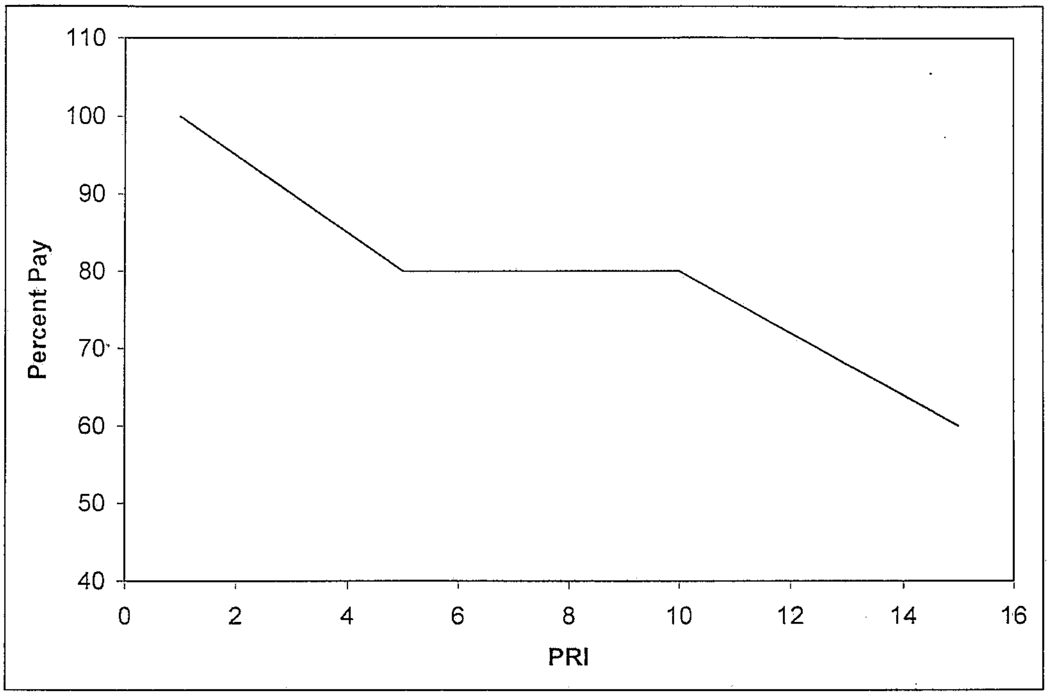


Figure 5.2 - Combination Continuous Function/Step Function Relationship Between Pay Factor and PRI

The experience of ALDOT, and many other States, is that too many pavement segments are currently receiving higher pay factors than warranted. What is required is new pay scales set at levels that reward exceptional pavements. At the same time the pay scale cannot be set so stringent that acceptable pavement segments are penalized. To determine where to set these levels, it is necessary to decide what percentage of pavements should receive bonuses and what percentage of pavements should receive penalties. Ultimately this will be the decision of ALDOT. For the purpose of this research a variety of different pay scale proposals will be presented that will produce different percentages of segments that receive bonuses and penalties.

PERCENTILE VALUES

To determine which PRI values to use for establishing the bonus and penalty ranges it is necessary to find what percentages of all the pavement segments fall above and below the PRI values. When considering the overall distribution of PRI values, each value corresponds to a certain percentile of that distribution. Therefore, if there is a certain percentage of segments that are to receive bonus payments, the PRI value to set the bonus range at can be determined by finding the PRI value that corresponded to that percentile. Since the percentages to use for determining bonus and penalty ranges are not specified it is necessary to determine which PRI values correspond to a variety of different percentiles. This enables the identification of natural break points that can establish bonus and penalty range values; or they can be set at specified percentile levels (i.e. 10% receive bonuses).

Formulation of New Pay Factors

The new bonuses and penalties for contractor pay were determined through an examination of the profile indexes of 330 lane miles of highway. Manual reductions, calculated and provided by ALDOT, were analyzed along with the computerized reductions performed by ProScan based on a blanking band of 0.2 inches and a scallop resolution of 0.5 inches. PRI values were reported using the manual method for each 0.1 lane mile. The first step in identifying data outliers was to determine the mean and standard deviation for each lane for each project. An allowable range of the mean plus two standard deviations for each lane of each project was calculated, and then values exceeding this upper limit were removed. This process was repeated until no outliers could be identified. Typically a lower limit would also be calculated, however, in this case the mean was typically only one standard deviation above the 0.0 PRI value (for 0.2 inch blanking band).

This same approach was used to identify outliers in the ProScan data. A comparison of the mean and standard deviations for both the manual and ProScan reduction are shown below.

	Mean	Standard Deviation
Manual Reduction	1.90	2.20
ProScan	1.50	2.20

Suggestions for the revised smoothness specification are based on several assumptions. First, smoothness values statistically greater than the normal (average) ALDOT hot mix asphalt (HMA) pavement smoothness indicate that an incentive is warranted. This limit is set at one standard deviation (2.20 PRI) above the grand average manual method smoothness value of 1.90 PRI. This sets the risk for the agency at about fifteen percent (15%) for paying an incentive for a standard smoothness. Since 1.90 minus 2.20 would be a negative number, the lowest value reported for this test, using the 0.2 inch blanking band, of 0.0 should be used to indicate the extra quality.

Second, the mean Alabama HMA smoothness values of 1.90 (manual method) and 1.50 (ProScan) were averaged to obtain a value of 1.70. Since the standard deviation for both methods was the same, 2.20 PRI was added to this value to obtain a value of 3.90 PRI. This value represents a seller's risk of about 15% of having a pay adjustment assessed to an acceptable HMA smoothness.

Lastly, subsequent pay factor percentages and increments were kept the same. Considerably more information as to the initial PRI and subsequent loss of ridability is needed before these percentages can be adjusted.

Table 5.1 - Suggested Pay Factors

Pay–out	New	Old
105%	0.0	Under 3.0
100%	0.1 - 3.9	3.0 - 6.0
95%	4.0 - 5.9	6.0 - 8.0
90%	6.0 - 7.9	8.0 - 10.0
Unacceptable	Over 7.9	Over 10.0

Effect of New Pay Factor Adjustment

The new pay factors were and applied to the profile indexes for each section to obtain the resulting pay adjustment. With the adjustment, it was determined that ALDOT would have paid only 96.8% of the bid price for the paving projects that brought 102% pay under the old step-wise pay function. The majority of the adjustment occurred in the bonus range of the pay scale with a limited number of sections migrating into the penalty range, as shown in Figure 5.3.

The lowest PRI value that can be attained with the 0.2 blanking band is 0.0. This eliminates the ability to achieve the desired linear/stepwise combination function for the new pay scale. It is recommended that a null, or 0.0 blanking band be used in order to

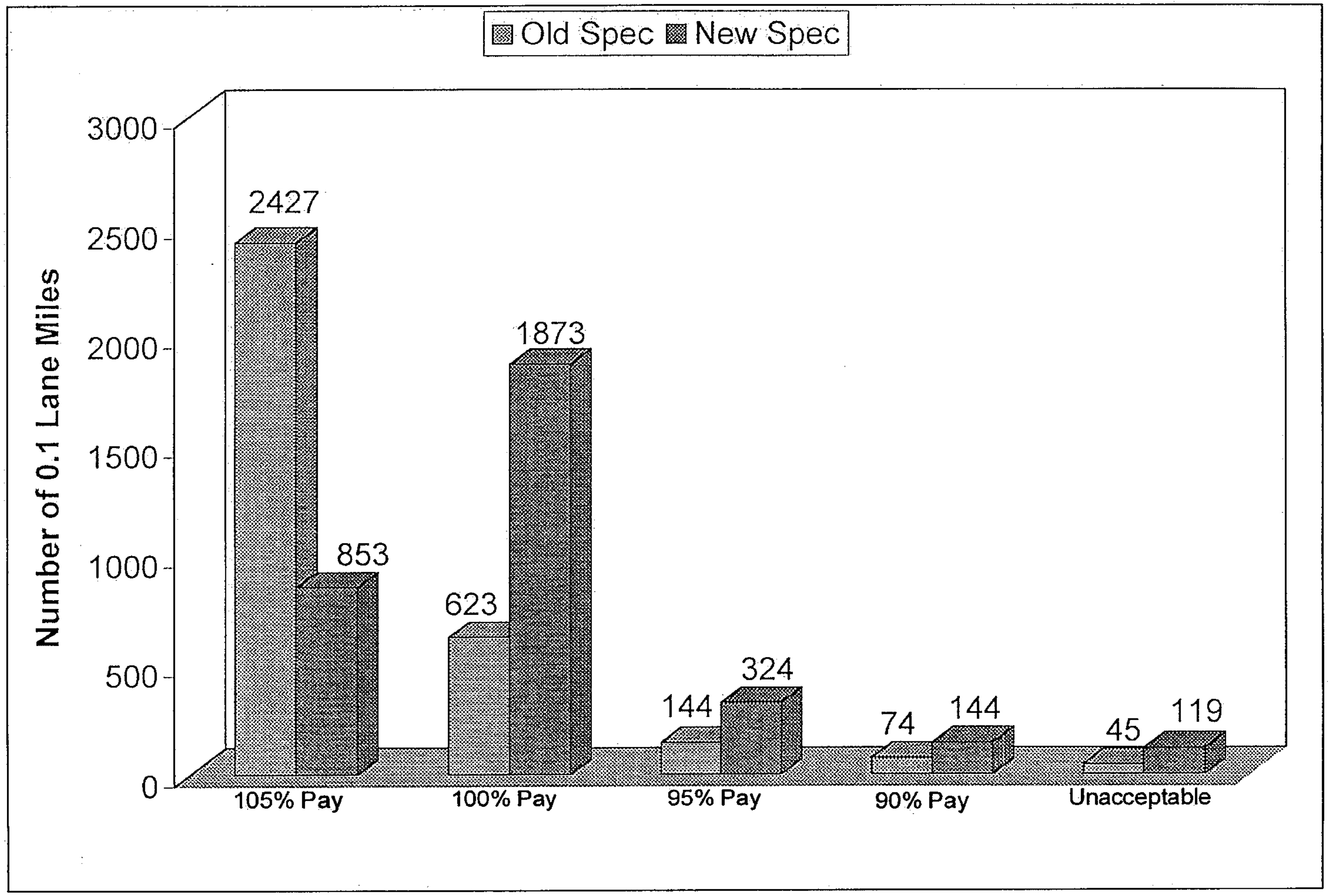


Figure 5.3 - Comparison of Performance Incentives Between Old and New Pay Factors

eliminate this problem. Figure 5.4 was generated using data from the NCAT test track in Opelika, AL. It shows that the 0.2 blanking band is well correlated with the 0.0 blanking band. Using the correlation equation, a new specification can be developed that will allow for a graduated pay scale in the incentive range, creating the linear/stepwise combination. The y-intercept from the line for the 0.0 blanking band (approximately 14.7) becomes the highest PRI value for the bonus range. A PRI just greater (14.8) is the lowest value in the100% pay range. This range is the middle step of the pay function found in figure 5.5. The remaining values of the suggested pay factors for a 0.0 blanking band are found below in Table 5.2.

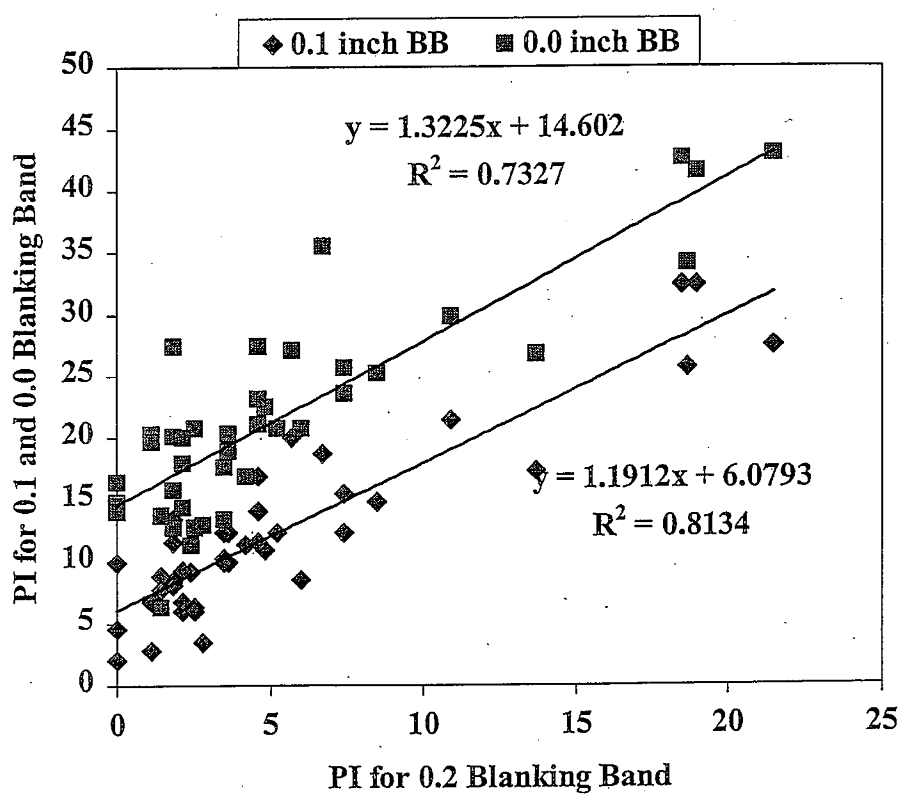


Figure 5.4 - Formulation of 0.0 Blanking Band Pay Function

Pay-out	PRI Range
100% to 105% max	0.0 to 14.7
100%	14.8 to 20.0
90% to 100%	20.1 to 26.0
Unacceptable	greater than 26.0

Table 5.2 - Suggested Pay Factors for 0.0 Blanking Band

The suggested pay function (shown in figure 4.5) developed from the table above becomes the following:

Bonus:

Percent Pay = -1.667 * PRI + 124.5

Penalty:

Percent Pay = -1.667 * PRI + 133.33

Example 1:

<u>Bonus PRI</u>
PRI = 13.0; Percent Pay = -1.667 (13) + 124.5 = 102.83%
<u>Penalty PRI</u>
PRI = 23.5; Percent Pay = -1.667 (23.5) + 133.33 = 94.16%

Notice that the slope of the bonus and penalty portions of the incentive diagram are equal. The result is that the same monetary increment is provided as a bonus or penalty for a unit increase or decrease in the PRI value. (see following calculation).

Example 2:

<u>Bonus PRI</u>
PRI = 14.7 - 2.0 = 12.7 Percent Pay = -1.667 (12.7) + 124.5 = 103.3%
<u>Penalty PRI</u>
PRI = 20.0 + 2.0 = 22.0 Percent Pay = -1.667 (22.0) + 133.33 = 96.7%
NOTE: Both differences in percent are 3.3

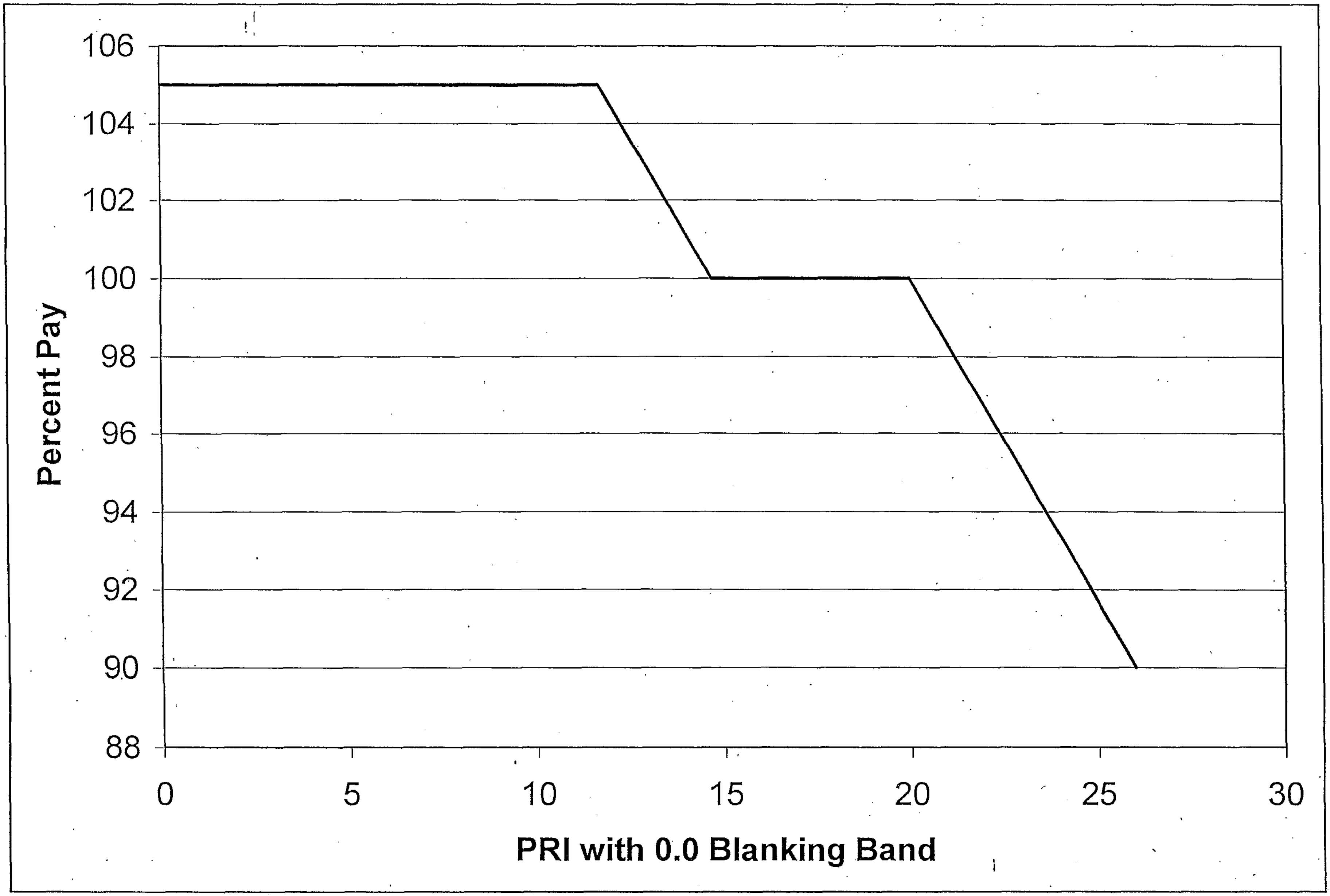


Figure 5.5 - Suggested Pay Function

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