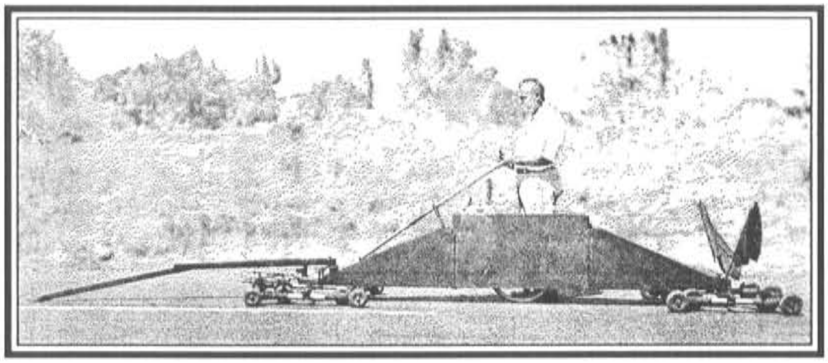
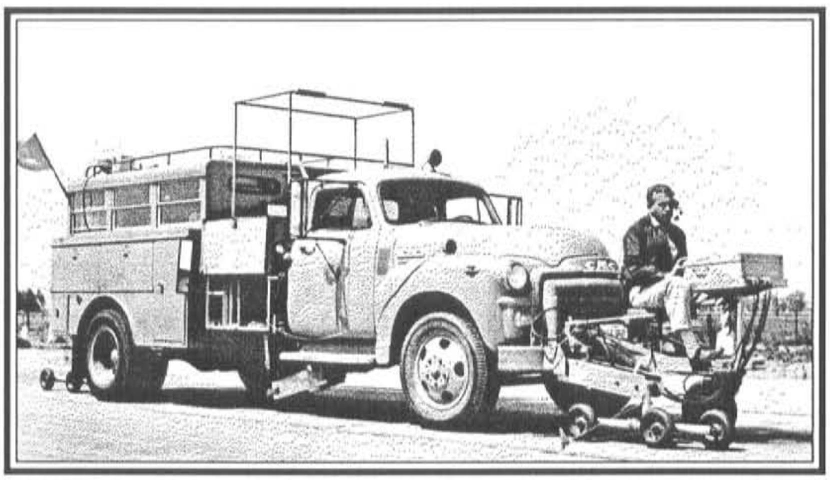
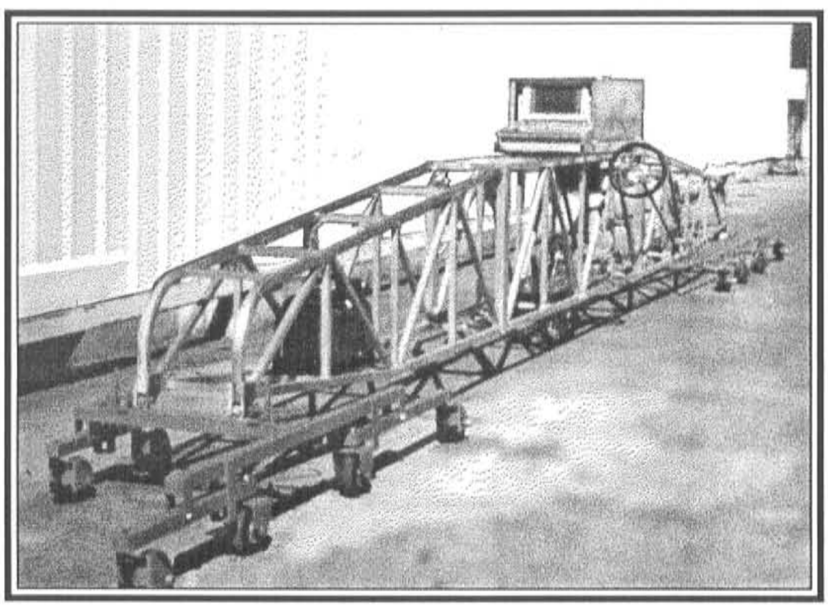
A HALF CENTURY WITH THE CALIFORNIA PROFILOGRAPH







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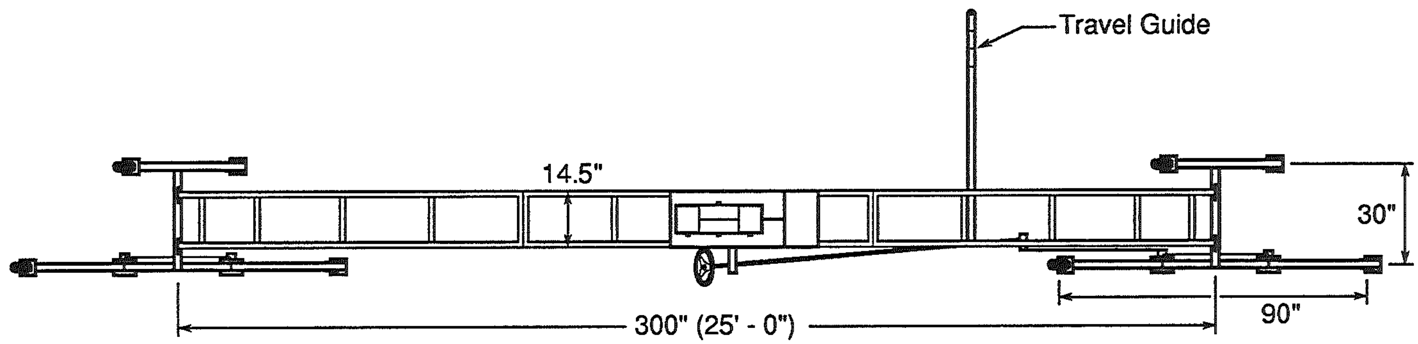
SCHEMATIC OF THE CALIFORNIA PROFILOGRAPH

(From McCracken Profile Reader - Product Bulletin)



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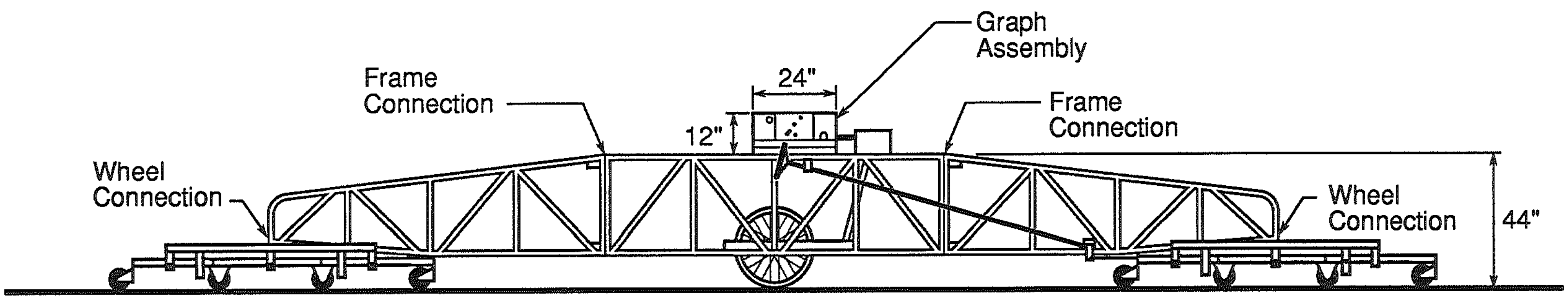

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16. Abstract

This study was performed to establish equipment and operator variability for mechanical and computerized California profilographs. Future work, based on testing conducted during this study, should develop precision and bias statements for profilographs.

The research consists of two phases. Phase I, reported herein, provided a literature review, performed the field testing and conducted the statistical anlysis. The historical development of the profilograph and California test procedures and specifications were evaluated in relationship to todays incentive/disincentive specifications. Additionally, equipment parameters which influence test variability were reviewed.

Two field experiments were conducted. The first experiment, designed to evaluate variability, consisted of a 4x4x2 randomized block design with replication. Two levels of pavement roughness, four operators, and four profilogrphs were utilized. The second experiment, designed to evaluate the effects of data filter settings on profile index obtained with computerized profilographs, consisted of a 3x2x2x2 randomized block design with replication. Two levels of pavement roughness, two computerized profilographs, two operataors, and three data filter settings were used.

The results of the study indicated that the average repeatability was 0.75 inches/mile and 0.56 inches/mile for the rough and smooth track conditions, respectfully.

The average repeatability for an operator performing trace reduction was 0.94 inches/mile for one device and 1.72 inches/mile for a second device.

The data filter setting used on computerized profilographs has a significant affect on the resulting profilo index. For each 1000 unit change in the data filter setting, a 7% reduction in the profile index was obtained when compared to the manufacturers recommended value of 8000.

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Registered Professional Engineer (Civil)
Certificate No. 13499
Larry A. Scofield
Date Signed 5/28/92
Arizona, U.S.A.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

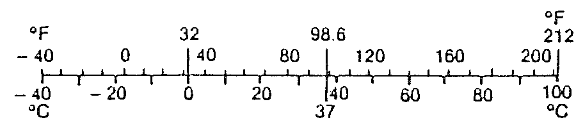
Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimetres	mm
ft	feet	0.305	metres	m
yd	yards	0.914	metres	m
mi	miles	1.61	kilometres	km
		AREA		
in^2	square inches	645.2	millimetres squared	mm^2
ft^2	square feet	0.093	metres squared	m^2
yd^2	square yards	0.836	metres squared	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	kilometres squared	km^2
		VOLUME		
fl oz	fluid ounces	29.57	millilitres	mL
gal	gallons	3.785	litres	L
ft^3	cubic feet	0.028	metres cubed	m^3
yd^3	cubic yards	0.765	metres cubed	m^3

NOTE: Volumes greater than 1000 L shall be shown in m^3.

Symbol	When You Know	Multiply By	To Find	Symbol
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams	Mg
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5(F-32)/9	Celcius temperature	°C

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimetres	0.039	inches	in
m	metres	3.28	feet	ft
m	metres	1.09	yards	yd
km	kilometres	0.621	miles	mi
		AREA		
mm^2	millimetres squared	0.0016	square inches	in^2
m^2	metres squared	10.764	square feet	ft^2
ha	hectares	2.47	acres	ac
km^2	kilometres squared	0.386	square miles	mi^2
		VOLUME		
mL	millilitres	0.034	fluid ounces	fl oz
L	litres	0.264	gallons	gal
m^3	metres cubed	35.315	cubic feet	ft^3
m^3	metres cubed	1.308	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.205	pounds	lb
Mg	megagrams	1.102	short tons (2000 lb)	T
		TEMPERATURE (exact)		
°C	Celcius temperature	1.8C + 32	Fahrenheit temperature	°F



* SI is the symbol for the International System of Measurement

(Revised April 1989)

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A HALF CENTURY WITH THE CALIFORNIA PROFILOGRAPH

I INTRODUCTION

The construction of newly paved roadways has seen an increased interest in attaining smoother and smoother surfaces. Results from a recently reported survey indicated that of the 36 states reviewed, 80% utilized smoothness criteria[1]. In the 1987 AASHTO survey 53% of the states utilizing profilographs for acceptance of concrete pavements used incentive and disincentive specifications[2]. The incentive/disincentive value typically ranged from 1% to 5% of the bid item price.

The relatively high incentives now possible with many of the current profilograph specifications places an ever increasing importance on the accuracy and repeatability of profilograph test equipment. Variability in test results can significantly affect contractor payments.

Accurate measurement of pavement roughness arises from the need for pavements to provide both ride comfort and resistance to damage resulting from the dynamic interaction of wheel loadings with the pavement structure. These two requirements generally are met by constructing smooth roadways. Roughness, however, is a function of the wavelengths of the surface irregularities. Devices used for determining pavement roughness must be able to accurately measure roughness over the spectrum of wavelengths existing in pavement surfaces.

II DEVELOPMENT OF ROUGHNESS TESTING

Test Equipment Development

The earliest reported smoothness testing device is Brown's Viagraph utilized before the turn of the century[3]. This device, which consisted of a beam 12 ft. long by nine inches wide, recorded the roadway profile and provided a numerical index of the unevenness of the roadway. Macadam roadways of this era were considered acceptable if they attained a "standard of fitness" or smoothness of 15 ft. of unevenness per mile.

The current California profilograph reportedly evolved from the Roughograph[4]. This device consisted of a five foot beam supported by wheels on each end and was used for locating and marking bumps in the pavement. Specifications during this time required bump detection by means of a 5 ft. straightedge.

It wasn't until approximately 1940 that the first "profilograph" type device was constructed by the California Division of Highways. This device consisted of a 10 ft. long wooden beam supported by 16 wheels (See Figure 1). Several criteria were fulfilled by this design[5]: (1) "The instrument should have a length or wheel base (13 ft. overall) approximately the same as a typical automobile in order that the roughness should be recorded with reference to a motor vehicle plane and not with reference to a continuous plane."; (2) "The instrument should be supported by a multiplicity of wheels, at least 16, mounted on compensating axles in order to provide a datum plane about the wheel base of an average car parallel to the local pavement contour but which would be virtually independent of minor inequalities."; (3) "The apparatus may be dismantled into units not over 40 inches in length and the entire assembly readily stowed in the trunk and tonneau of a small sedan." Reportedly, the selection of the 10 ft. length of frame was due to the fact that California specifications for pavement finish referred to the amount of departure from a 10 ft. straightedge placed on the surface[6].

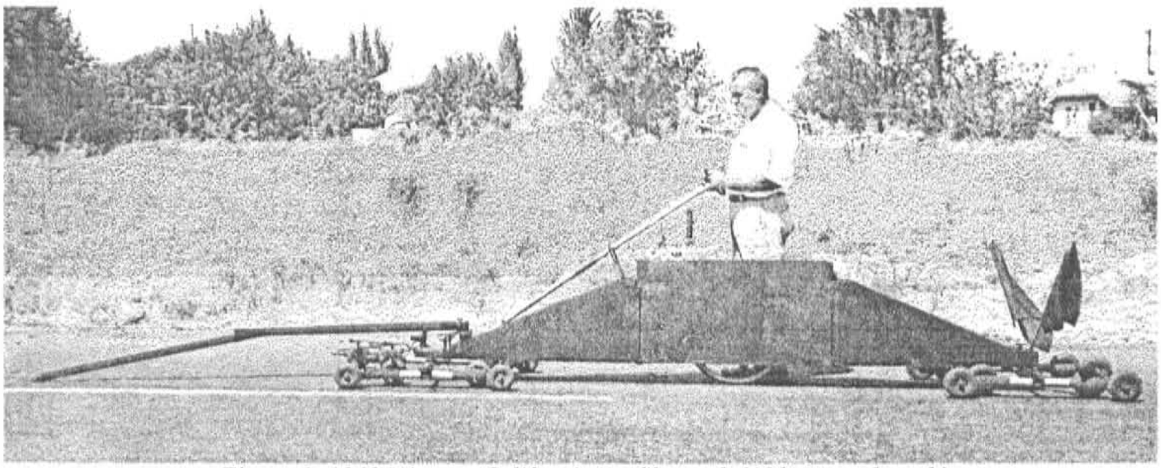


Figure 1 1940 Vintage California Profilograph (10ft. Beam length)

To verify the accuracy of this device, profilograms (i.e. profile traces) were compared to rod and level surveys performed at 5 ft. intervals and to profiles generated by stretching piano wire over the surface and measuring the deviations with a scale. In reporting on the accuracies of this comparison Francis Hveem, the developer of the profilograph, stated that: "agreement appeared to be sufficiently close for all practical purposes but unanswered questions always persisted as to the exact shape of the bumps in the pavement."

This 10 ft. device appears to have been used for most of California's profilograph work until about 1955 when California constructed a mobile profilograph based upon a 25 ft. beam (See Figure 2). This new device was developed as a result of the general increase in traffic speed and the trend toward vehicles with longer wheelbases. The 25 ft. length was selected more or less arbitrarily. This mobile system was constructed around a two-ton truck. A total of ten boogie wheels were used with the 25 ft. beam attached to the truck. The unit obtained profile traces only in the outer wheel path.

While the mobile unit proved very useful for network level evaluations, it was too heavy to operate on newly constructed pavements for construction control purposes. Subsequently, a 25 ft. hand-propelled unit was constructed with a tubular aluminum frame. The aluminum frame was used to overcome problems with wind experienced with the earlier plywood models, but it was too costly for practical use.

Figure 2 California Profilograph Showing Recording Console in Elevated Position

In 1957 a hand-operated plywood profilograph with metal edging was constructed with a 25 ft. beam length and a total of 10 wheels (See Figure 3). The first aluminum square-frame profilograph was constructed around 1962. It is believed that this may have been the origin of the twelve-wheeled system still commonly used today.

In 1983 Caltrans did additional research and revised the profilograph so that only four wheels were used[2]. During the development of the four-wheeled system, comparisons were made between the profilograms obtained with the 12 wheel and 4 wheel profilographs. Caltrans found that only subtle differences in profile features existed and no differences in profile index were obtained[2].

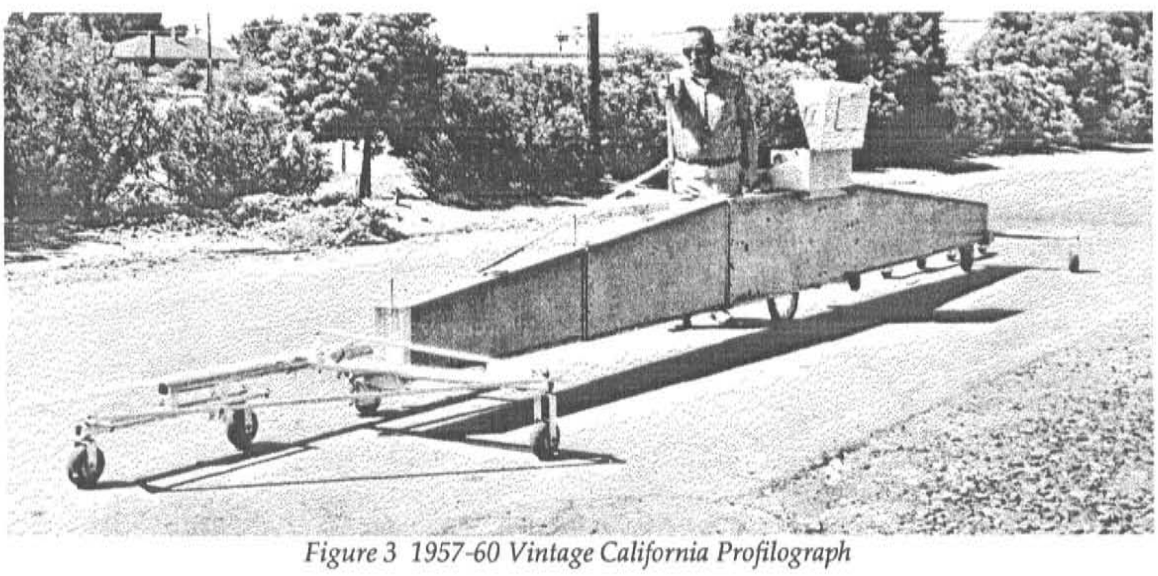


Figure 3 1957-60 Vintage California Profilograph

During almost fifty years of use, the California profilograph has seen many changes. The beam length has varied from 10 ft. to 25 ft. It has been a mobile unit and a hand-propelled unit. There have been as many as 16 wheels and as few as four. It has been constructed of wood, steel, and aluminum, and has been assembled in three to five sections. The model most prevalent in the industry today resembles the 1962 twelve-wheel profilograph. During the mid 1980's the recording device was computerized by Cox and Sons, Inc. Both mechanical and computerized versions (automated) are currently available in the industry.

III ROUGHNESS SPECIFICATION DEVELOPMENT

California State-wide Roughness Survey

During the spring and summer of 1956 the California Department of Highways surveyed approximately 60 roadway miles of pavements, consisting of 34 separate sections, with their mobile profilograph[6]. The 34 sections were selected by nine Districts as representing both smooth and rough roadways. Seventeen sections were asphalt concrete (AC) pavements and 17 were concrete pavements (PCCP). The selected pavements consisted of both two lane and four lane roadways. Profilograph traces were obtained in the outer wheel path approximately 30 inches from the edge of pavement and recorded in the direction of traffic. At the time of testing the profilograph operators recorded their personal observations regarding relative roughness of the roadways as they drove over them in a car. These subjective observations (i.e. "jury" evaluations) were subsequently compared to numerical indexes established from profilograph traces.

Upon completion of the survey, 15 sections of PCCP and 11 sections of AC pavements were chosen for further study. These sections were selected because clear examples of both rough and smooth pavements could be classified from among them.

The purpose of the state-wide survey was to develop a numerical index which would relate to a "jury" evaluation of rough and smooth roadways. This would allow a profilograph to quantitatively evaluate pavement profiles in terms of human perceptions of rough and smooth. During this study it was recognized that "classifications of ride comfort must necessarily be broad because in addition to the factor of personal reactions, speed and type of vehicle were also important parameters[6]."

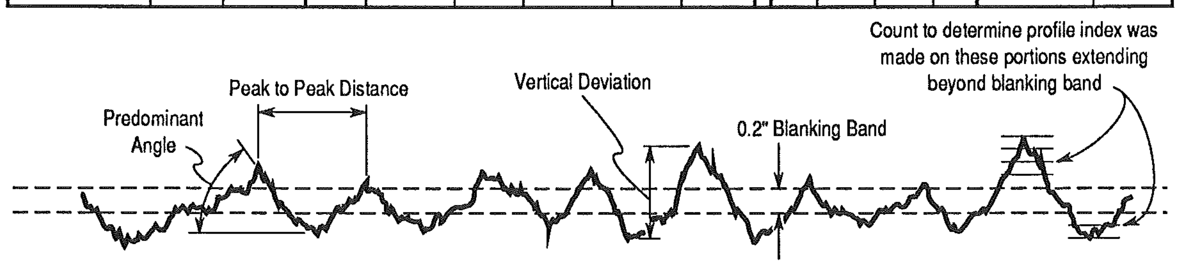
Profilogram Trace Reduction Procedures

The profilogram traces obtained from the 26 sections chosen for further evaluation from the state-wide survey were analyzed in detail. To analyze these profilogram traces several features were evaluated: the size of vertical deviation, the peak to peak distance between vertical deviations, and the predominant angle of the peak deviation. These features are shown in Table 1. During the analysis of these traces, Don Spellman of the California Division of Highways conceived the idea of evaluating vertical deviations only after blanking out those portions of the profile showing only minor inequalities. This concept was based on the fact that profiles from rough roads typically exhibited short waves or scallops having ordinates over 3/8 inch. The 0.2 inch blanking band concept was arbitrarily selected. A comparison of the summation of the vertical deviations after applying the 0.2 inch blanking process is also shown in Table 1. It was believed that the small inequalities which were blanked out had little effect on ride comfort. The blanking band process was thus established in 1957. It should be noted that the blanking band concept was developed to facilitate or expedite the trace reduction process. It appears that this was the most efficient way to get a numerical index which related to subjective ride quality. It is not known whether this method had the best correlation with subjective ride quality of the methods studied. With the introduction of the 0.2 inch blanking, the summary statistic representing the results of this procedure was termed the profile index. This represented the summation of the deviations in excess of the 0.2 inch blanking band.

The pavement sections evaluated during the state-wide survey ranged in profile index from 0.2 inches / mile to 90 inches / mile. It was determined that new concrete pavements and old ones in good condition ranged between 2 inches / mile and 10 inches / mile. Rough concrete pavement was considered to be 40 inches / mile and over. It was also observed that one mile of profile was necessary to adequately represent a pavement's ride quality. Even then some profiles exhibited wide differences in appearance and were not well represented by average values. All the PCCP sections tested during the 1956 state-wide survey were constructed with fixed form methods.

TABLE 1 PROFILE ANALYSIS SUMMARY SHEET-PCC PAVEMENTS (FROM REFERENCE 3)

County, Route & Section	Length Miles	Classification	Size of Vertical Deviations (Log Scale) 1/4 3/8 1/2 3/4 1	Peak to Peak Distance 10 ft 20 ft 30 ft 40 ft	Predominant Angle, Degree	Profile Index (0.2")
VI-Fre-4-A	2.1	Smooth			Low	0.2
V-S.B-2-F	1.1	Smooth			5-15	3.8
IV-Ala-69-Berk	1.0	Smooth			Low	5.2
VIII-SBd-26-D	2.0	Smooth				
XI-S.D-199-Cor	2.2	Smooth			10-15	2.6
V-Mon-56-I	1.2	Smooth			10-15	9.7
I-Hum-1-Ftna	0.3	Fair			30-45	19.0
I-Men-1-Uki	0.5	Fair			45	13.8
VIII-Riv-19-B	1.0	Fair				9.7
IV-Ala-69-E	1.5	Fair			45-60	16.4
XI-S.D-2-S.D	0.7	Fair			45-60	21.9
IV-SC1-2-C	2.2	Rough			45-60	58.5
III-Gle-7-A	4.5	Rough			50-70	64.1
VI-Tul-4-B	2.2	Rough			45-60	44.7
V-Mon-2-Sal	0.7	Rough			30-60	



Slip Form Paving Testing

In 1958 the California Department of Highways took their mobile profilograph to Colorado to measure the roughness of one of the early slip-formed pavements. Since the PCCP sections previously evaluated had been of fixed form construction, this allowed California to assess the ride qualities produced by slip-form techniques.

Construction Specification Development

The first reported use of the 7 inch per mile profilograph specification appears to have been in 1958[7]. Between 1959 and 1960 approximately 12 projects used the newly developed specification[7]. The first California Standard Specification with the 7 inch per mile profile index requirement was published in 1960.

The origin of the 7 inch per mile profile index requirement is uncertain at this time. Although it is assumed that this limit was also a result of the state-wide study conducted in 1956, it has not been verified. No information has been discovered as to the reason for the selection of the 7 inch per mile requirement or what distribution of projects were constructed to that quality at the time of the specification origin. It is quite possible that surveys in addition to the 1956 survey were conducted to establish the new profile index requirement. However, if the 1956 survey was used and only the 15 projects shown in Table 1 analyzed, limited information would have been available to select the 7 inch value. Eighty percent of the pavements designated as smooth in Table 1 were below the 7 inch requirement with a mean of approximately 4.3 inches per mile.

This may have been what prompted Francis Hveem to state in 1959: "In California many new pavements, either of asphalt or concrete, have been constructed with current methods to profile indexes well below 5. In order to permit contractors to use a greater variety of equipment and finishing methods, several experimental contracts were awarded stipulating that concrete pavements may be finished by any means that the contractor may elect provided the profile index of the completed work does not exceed 7 when measured along each outer wheelpath."[8]

The 1960 California specification stated that "the profile index, as measured by the profilograph, for any one-tenth mile section shall not exceed the rate of 7.0 inches per mile along any line parallel to the edge of pavement." Testing was performed in the direction of paving, 3 ft. in from the edge of pavement and at the lane lines. This resulted in three measurement tests conducted for a 24 ft. wide pavement and four measurements for a 36 ft. wide pavement.

The utilization of the 0.1 mile analysis interval at the time of the 1960 specification is also of unknown origin. However, it is no doubt a result of the wide differences found in a pavement's ride quality such as described in the 1956 state-wide study.

The original specification and test procedures developed in 1960 are still widely used today. The specification appears to have been established on a limited number of pavement sections built with fixed form construction, from profiles obtained on the outer wheel path, in the direction of traffic, with a mobile profilograph.

Typical Vehicle Operating Characteristics During Specification Development

The correlation between subjective ride quality (i.e. the jury rating) and an objective numerical rating known as the profile index was established with vehicles from the mid 1950's and older. Passenger vehicles of this vintage typically had wheel bases on the order of 118 - 128 inches and weighed 4500 lbs[9]. Torsion bar suspension was introduced in 1957 and the infamous air bag suspension in 1958[10]. Independent front suspensions had only been produced since 1934 in America[10].

Truck types and suspensions were also quite different in those times. Figures 4 and 5 represent the frequency distribution of axle loads and vehicle types in 1948[11]. As can be seen 5 axle vehicles represented less than 5% of the fleet in the western states.

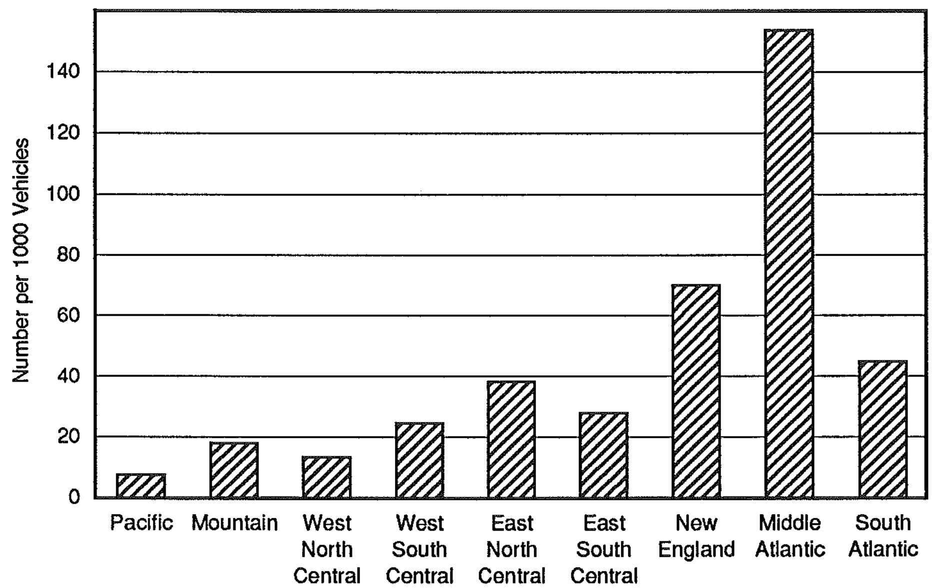


Figure 4 Frequency of Axle Loads of 20,000 lb. or More, Per 1,000 Vehicles, by Regions in 1948 (From Reference 11)

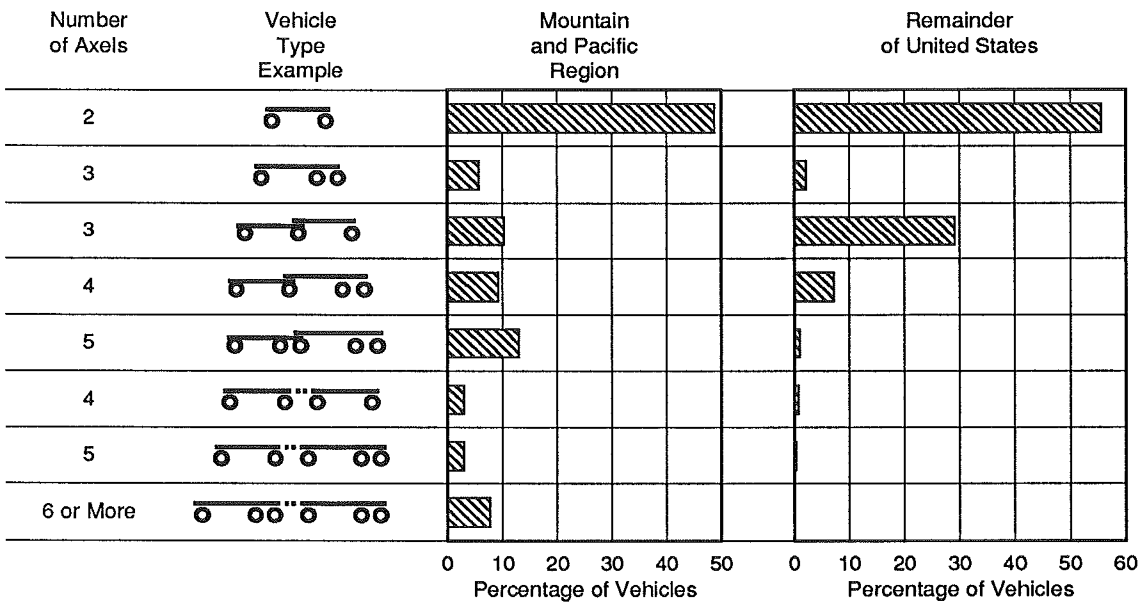


Figure 5 Percentage Distribution of Vehicles of Various Types (Exclusive of Two-Axle Single Tire Vehicles) in the West and the Remainder of the United States, in 1948 (From Reference 11)

Remembering that ride quality is necessary both from the standpoint of ride comfort and from minimizing pavement damage from wheel loadings, it is difficult to accept the 1950s standards as representative of today's needs.

IV CURRENT TECHNOLOGY

Available Test Equipment

In addition to the California type profilograph discussed herein two other profilograph styles exist; the Rainhart and Ames profilographs. The profilographs described in the preceding sections were all constructed by what is now CALTRANS. CALTRANS has always constructed its own devices.

California type profilographs have been available commercially from principally two major manufacturers. James Cox and Sons Inc. manufactured the mechanical profilograph from 1960 to 1983. They produced the first computerized version in 1985, but operational problems terminated its production again until 1988. Cox and Sons has produced the computerized version since 1988 (See Figure 6).

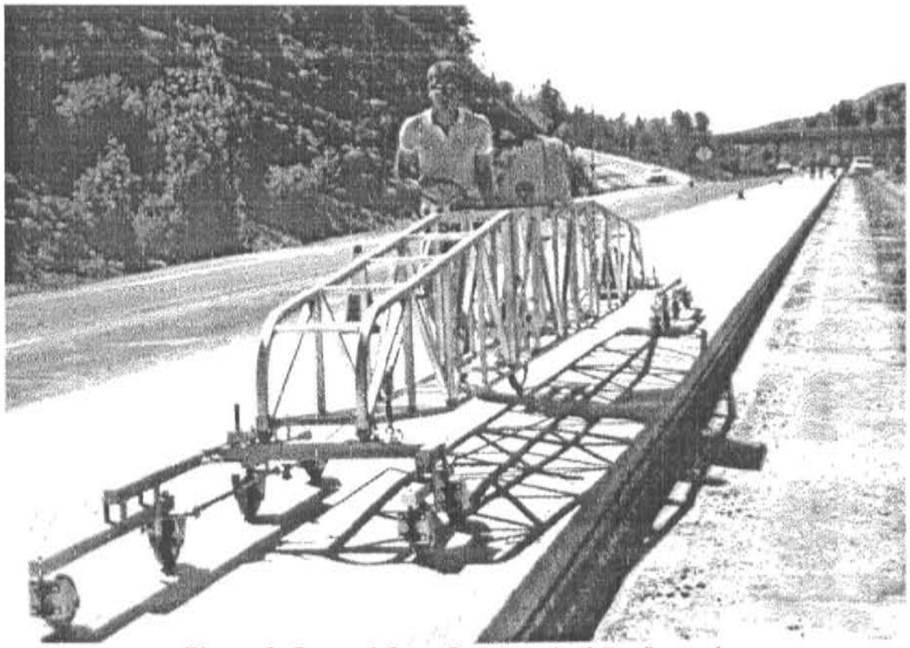


Figure 6 Cox and Sons Computerized Proflograph

The McCracken Pipe and Machinery Company is the only current manufacturer of a mechanical profilograph (California style). They began producing the mechanical unit in 1984 and produced their first computerized version in 1990 (See Figure 7).

Although subtle changes have occurred in some aspects of the California profilograph, it has remained essentially the same from about 1962 to 1988. When Cox and Sons introduced their computerized version, this marked the first major change to the industry in a quarter century.

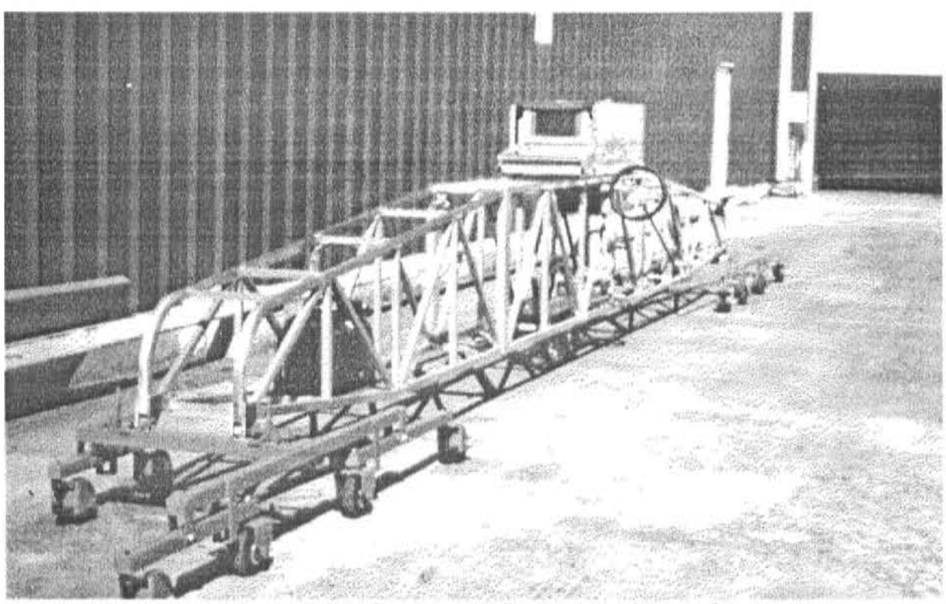


Figure 7 McCracken Mechanical Profilograph

The transition from the purely mechanical profilographs to the computerized profilographs has vastly improved the speed and convenience in obtaining and reducing profile traces. It has also, unfortunately, introduced significantly more controversy into the industry. In the past, mechanical devices were seemingly similar in appearance and operation. Most controversy surrounding the resultant profile traces and indexes focused on the condition of the equipment or the operators reduction of the trace. Although a continual problem, it was a situation which "seemed" correctable to most parties.

The introduction of the computerized or automated versions has introduced high technology into an industry which has remained essentially static for almost thirty years. In the past, profile traces were charted by the profilograph as the test was conducted. Upon completion of the field testing trace reduction was performed manually by the operator with a template in the office. The computerized versions digitize the profile signal and automatically analyze the profile index upon completion of testing. This is accomplished by processing the digitized signal through a low pass digital filter to smooth the trace. A least square regression is then performed to center the blanking band on the trace. These techniques should enable the automated equipment to be more reproducible since operator interpretation has been eliminated. However, it has created a black box analysis which is too often questioned.

Filtering Phenomenon

The Cox and Sons device uses two filters to process the profile signal. A "data filter" is used to smooth the trace by filtering out effects from surface texture and other vibrations not indicative of pavement roughness. This process is similar to what a manual operator does when he outlines his trace prior to interpretation. The second filter is the "null filter" which is used only when short radius curves are present. This filter centers the null band on the trace. This procedure is similar to manual methods which require centering the blanking band on short sections to provide valid interpretations. Both of these filters can have their settings specified prior to conducting testing. Different settings will produce markedly different profile index results.

Probably the first agency to investigate the effects of this filtering was the South Dakota Department of Transportation[12]. They used standard signal processing techniques to analyze the effects of the data filter. They determined the response of the filters at various wavelengths of roughness. This response is shown in Figure 8. At a wavelength of 1.6 ft. the signal is attenuated by approximately 70% while a wavelength of 8 feet is attenuated approximately 15%.

The effect of the filtering can also be shown by simulating a one inch block with a step function[12]. As shown in Figure 9 the profilograph trace, at a data filter setting of 8000, does not attain 95% of the height of a one inch block until the profilograph has travelled approximately three feet beyond the block. At a data filter setting of 4,000 the trace does not attain 95% of the one inch height until almost 6 feet away.

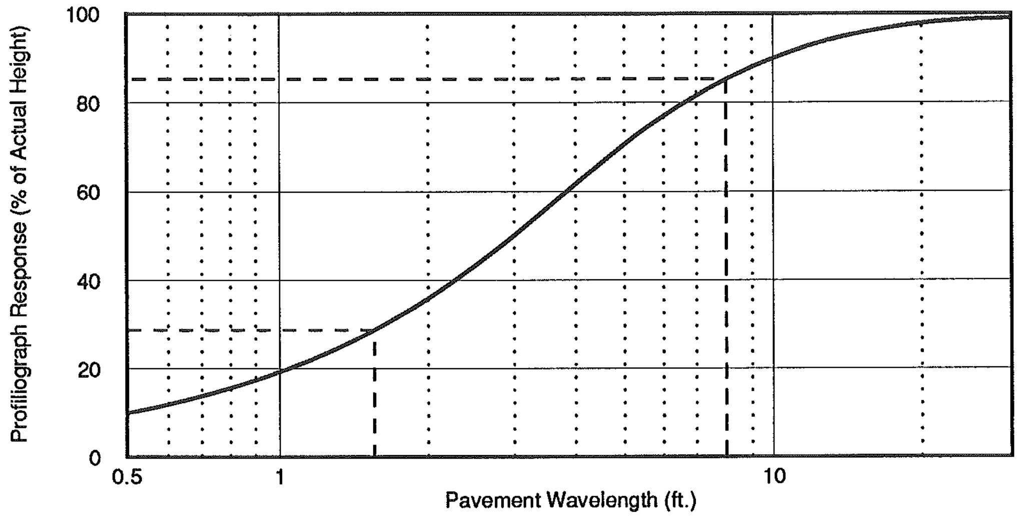


Figure 8 Response of Data Filter As a Function of Pavement Wavelength (N=8000) (From Ref. 12)

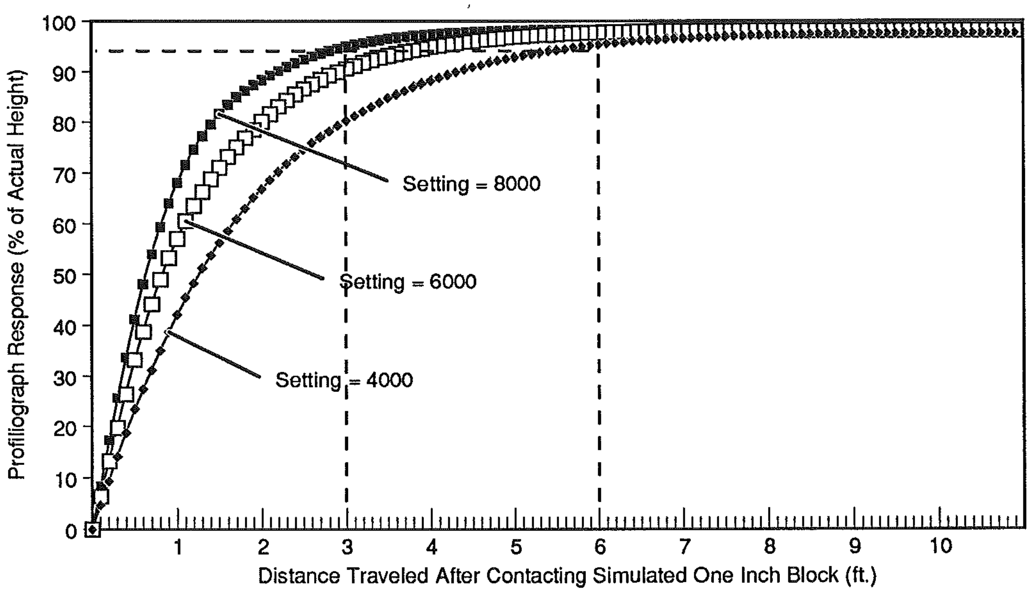


Figure 9 Effect of Data Filter Setting on Profiliograph Response to a One Inch Step Function (Simulated Block)

Frequency Response

The importance of signal filtering or profile attenuation should be discussed in relationship to the wavelengths present in pavement roughness. NCHRP report 275 indicates that subjective ride quality is best correlated with wavelengths between 1.6 ft. to 8 ft. for typical highway speeds[1]. Wavelengths which provide the greatest dynamic forces to the pavement structure range between 2 ft. and 32 ft. for typical highway speeds. Therefore, test equipment designed for measuring pavement smoothness should be sensitive to wavelengths from 1.6 ft. to 32 ft. Since the profilograph attenuates short wavelengths most, it is quite possible that the filtering would affect the measured profile index. However, this has not been verified from a practical standpoint. The amount of effect, if any, on profile index would depend upon the wavelengths present in the pavement surface. The profile index for pavements composed mainly of short wavelengths could significantly be affected while those comprised mostly of wavelengths greater than 10ft. would be almost unaffected.

Both profilograph manufacturers developed improved profile signal filters during 1991. Although these filters are not commercially available at the time of this report, at least one study was conducted to evaluate the practical difference between the original Cox data filter and the newer Cox signal filters[13]. The reported results suggest no practical difference between the original and the newer filters studied. This study did report that all the filters included bumps 18 inches or longer in the Profile Ride Index (PRI) computation. Test procedures generally require inclusion of only bumps 24 inches and longer.

Accuracy of Output

The discussion on filtering is based only on the Cox and Sons Model CS8200. Although it is believed that the McCracken system uses similar low pass filters this has not been confirmed. The McCracken system does provide at least one additional difference from the mechanical profilograph. Test procedures based upon California methods report excursions beyond the blanking band to the nearest 0.05 inch. This is also how the Cox CS8200 reports excursions. The McCracken system reports excursions to the nearest 0.01 inch. Accuracies to this level with manual methods would be tedious at best. Computer traces provide a convenient method to more accurately reduce the profile. If the automated profilograph systems can readily record profile to this accuracy, trace reduction should be performed at the 0.01 inch tolerance.

V FACTORS AFFECTING EQUIPMENT VARIABILITY

Frequency Response of Profilograph

Inherent in the design of the standard California profilograph are several limitations to accurate measurement of pavement profile. Due to the geometry of the system the profilograph amplifies some wavelengths while attenuating others. Figure 10 shows the actual and desired frequency response of a standard profilograph[1]. These responses should be considered in conjunction with the previous discussions on wavelengths affecting pavement ride quality. It is evident in Figure 10 that the profilograph attenuates some wavelengths and amplifies others. A wave length of 10 ft. is accurately reproduced while a wavelength of 20 ft. is amplified almost 60%.

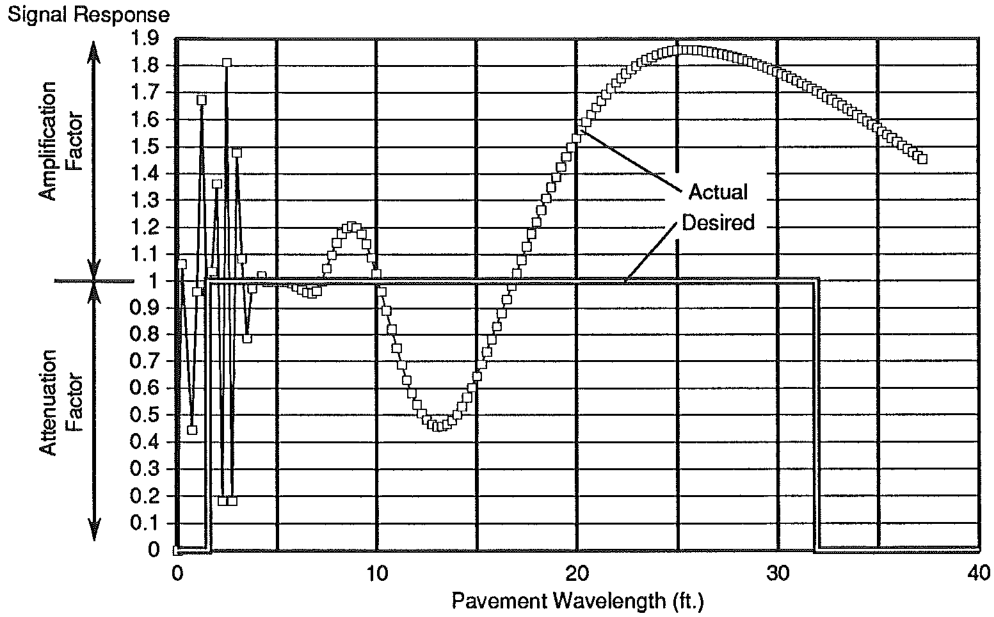


Figure 10 Desired and Actual Frequency Response of 12 Wheel Profilograph (From Reference 1)

Effect of Main Truss Length

Kulakowski and Wambold studied the effect of main truss length on profile accuracy at the Pennsylvania Transportation Institute (PTI)[1]. Figure 11 shows this effect for various wheel spacing configurations. As evident in Figure 11, the longer the main truss length the better approximation of the "true" roughness value by the profilograph. The PTI study reported that a 30 ft. main truss length was the optimum length for a profilograph.

During the development of the California Profilograph the effect of main truss length on measured profile was studied. Figure 12 indicates profile traces produced with different truss lengths. As shown, the resulting profile is affected by truss length.

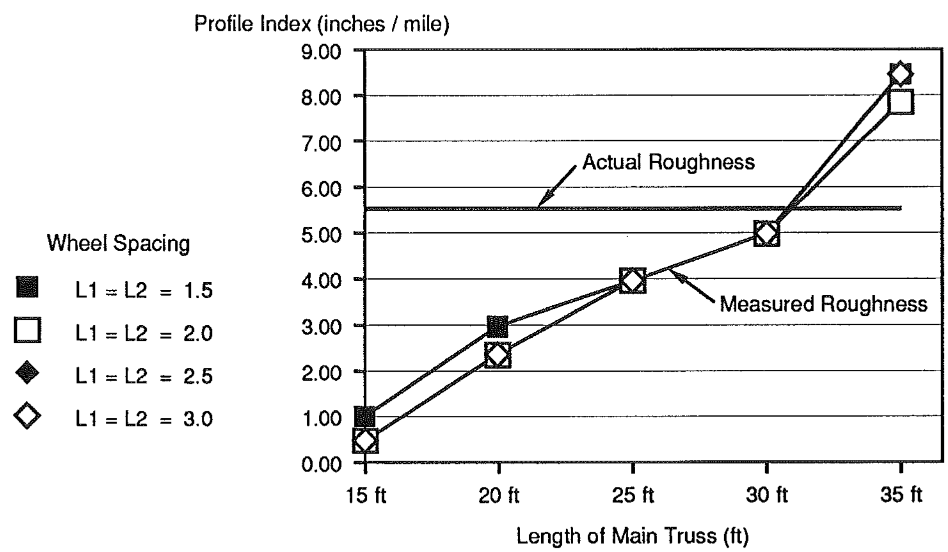


Figure 11 Effect of Length of Main Truss, L, and Spacing Between Supporting Wheels, L1, on Roughness Measurement (From Reference 1)

Effect of Number and Spacing of Wheels

Also shown in Figure 11 is the effect of the spacing between supporting wheels. This work, conducted by PTI, concluded that the spacing of the wheels had negligible effect on the profile index for wheel spacings between 1.5 ft. and 3.0 ft.[1].

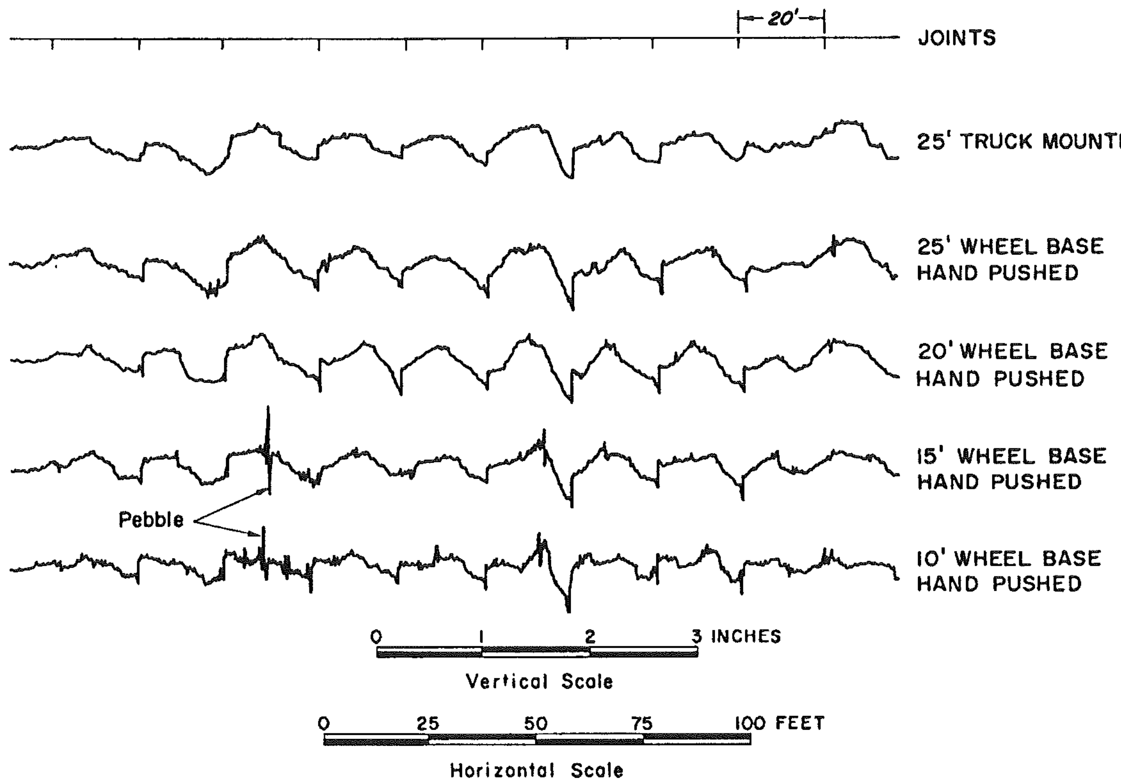


Figure 12 Effect of Truss Length on Profile Traces (From Reference 3)

The PTI study also evaluated the effect of the number of wheels on profile accuracy. Figure 13 indicates the results of this study. The PTI report stated that four to six wheels were sufficient. Their computer simulation supported the work of Caltrans who changed from the twelve wheel system to a four wheel system in 1983. The PTI report suggests that the change to a four wheel system would slightly increase the profile index. From a practical standpoint this was not found by Caltrans.

The reduction to the four wheel device was probably the most significant operational improvement in the profilograph since its inception. The four-wheeled device is significantly more convenient to operate.

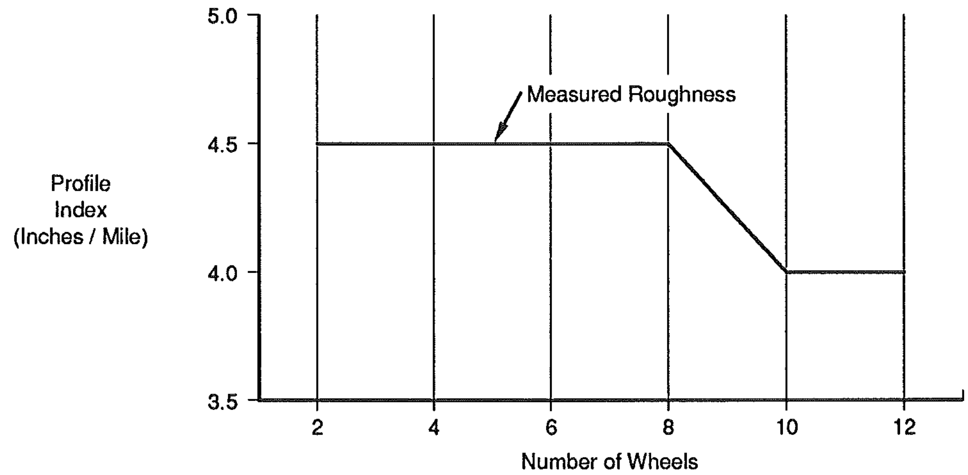


Figure 13 Effect of Number of Wheels on Roughness Measurement (Actual Roughness = 5.5 inches/mile) (From Reference 1)

Effect of Tire Wear and Eccentricity

Two other aspects studied in the PTI study were those of tire wear and eccentricity. The PTI researchers concluded that tire wear had an insignificant effect on the profile index while eccentricity had a significant effect. The PTI authors stated "...the eccentricity of the measuring wheel presents a serious problem when measuring pavement roughness."

The seriousness is evident in Figure 14. It should be noted that eccentricity always increases roughness. An eccentricity of less than 1/8 inch (i.e. 0.1 inches) increased the measured roughness from 4 inches/mile (no eccentricity) to 20 inches/mile. This clearly portrays the magnitude and seriousness of eccentricity. It is doubtful that eccentricities of 1/32 of an inch or less are readily discerned in the field, yet their effect on measured roughness is pronounced.

PTI described eccentricity of the measuring wheel as that "... which occurs when the wheel is suspended at a point displaced from its geometric center." This effect is different than that resulting from an out of round tire which is presumably more prevalent. The later condition was not analyzed in the PTI study.

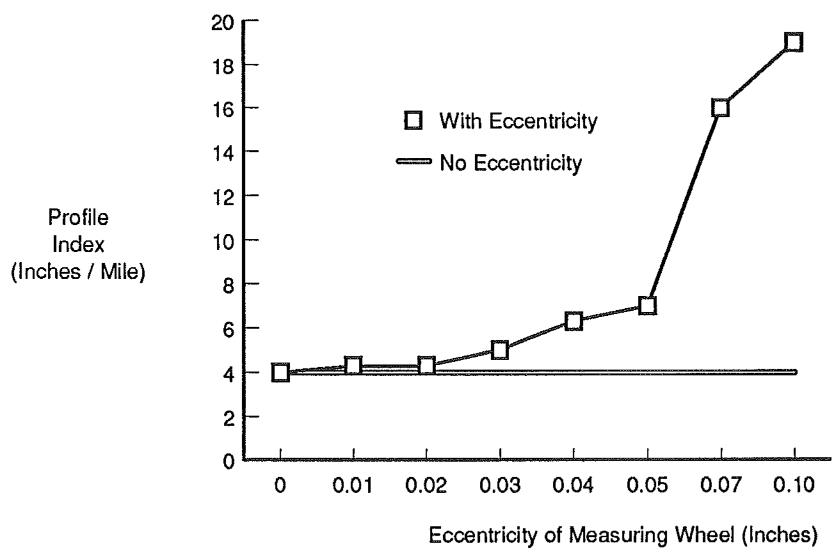


Figure 14 Effect of Measuring Wheel Eccentricity on Roughness Measurement (From Reference 1)

Effect of Mechanical Problems

In addition to the problems analyzed by PTI with computer simulations, mechanical problems with machine adjustments can affect profile index. The top profile trace in Figure 15 indicates a trace which occurred when the recording system was not properly adjusted. As can be seen some of the peaks are being clipped resulting in a lower than expected deviation. The lower trace is a profile of the same section of pavement with a different mechanical machine. Notice the significant amount of noise in the trace. Operators could potentially arrive at different values depending on whether these traces were outlined first.

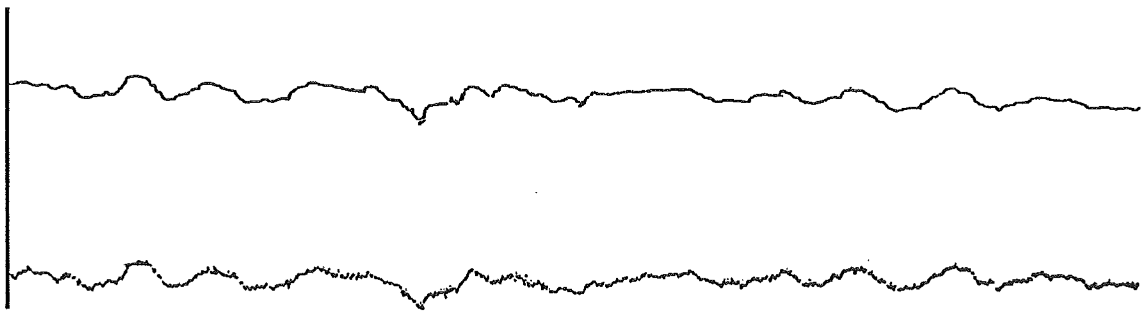


Figure 15 Profilogram Traces from Two Mechanical Machines

Effect of Tire Pressure

Tire inflation pressure can also be a source of variability. Although no data has been discovered to describe the magnitude of this affect, over or under inflated tires will produce different traveled distances. This probably affects mechanical devices more than automated devices since the later has a calibration factor which corrects the distance measuring capabilities. Mechanical systems are often calibrated to 0.5 ft. in 500 ft. and considered operational until the device misses the longitudinal distance by more than 5 ft. in 1000 ft.[14]. A study conducted by ARE Inc. concluded that the devices exhibited a distance measurement error of 4 ft. to 5 ft. in 1000 ft.[15]

VI OPERATIONAL PROBLEMS WITH MEASURING ROUGHNESS

In addition to the equipment problems discussed in the preceding section a number of operational concerns also exist when attempting to assign a roughness value to pavements. The following sections discuss these problems.

Slab Curling

In plain jointed PCCP pavements curling of the slabs occurs as a result of daily temperature and moisture / humidity variations. These variations cause slabs to curl upward or downward based upon existing gradients. Thin slabs are most susceptible to this problem. Figure 16 is an example of how a profile trace can be affected by curling. In the morning the trace indicates the curling of the slabs while in the afternoon the slab experienced little or no curling. The affect on the profile index is not shown because this data was collected with a 10 ft. profilograph prior to the development of the current trace reduction methods. It does point out the problem of obtaining measurements at different times of day. For example, pavements measured in the morning (when its cool) could very well be rougher than those measured in the late afternoon. This would be most noticeable with thin pavement sections. Although the pavement age at which curling affects roughness readings is not known, it is suprising that curling is evident in Figure 16 on a pavement which is only one week old.

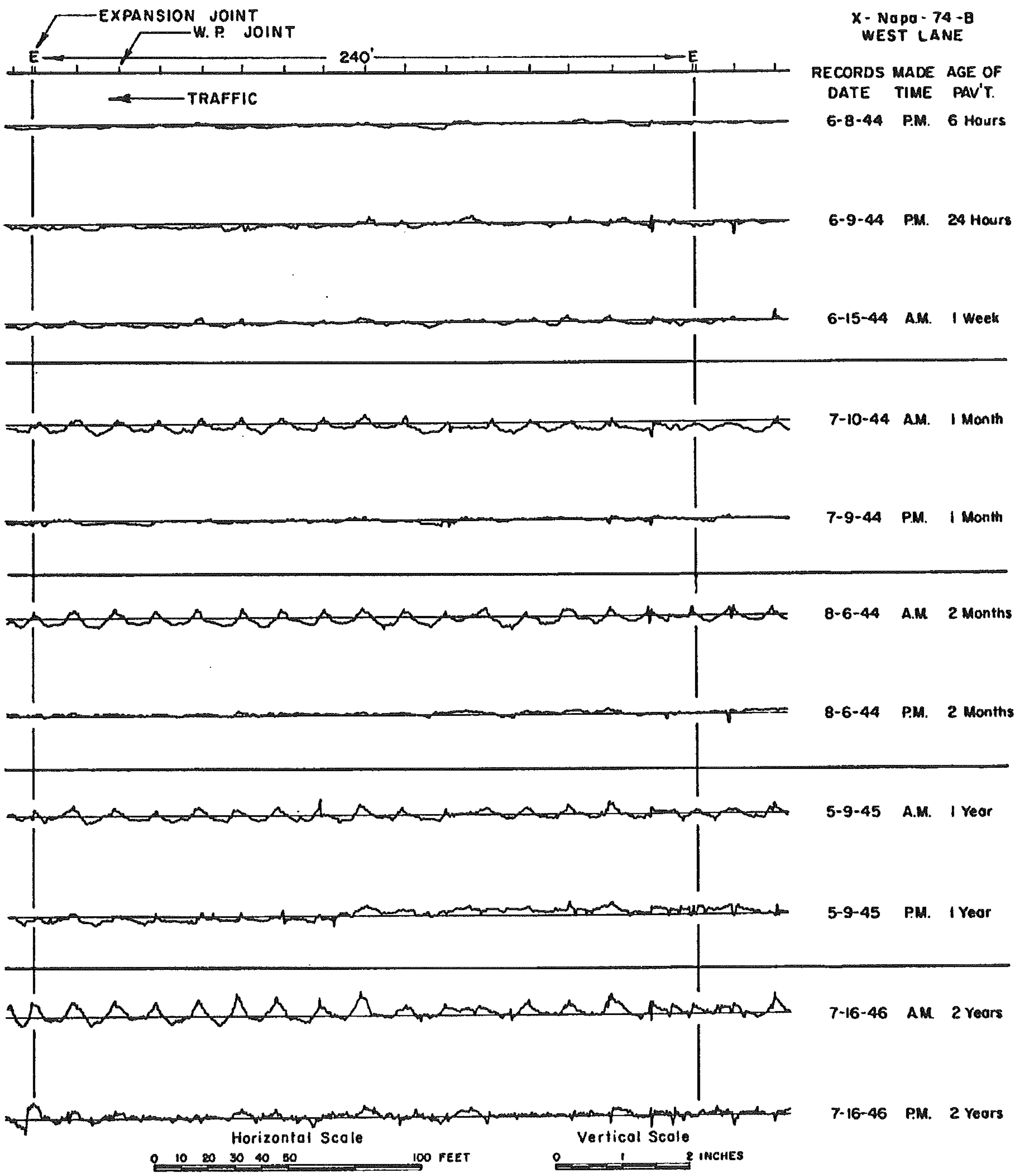


Figure 16 Effect of Slab Curling on Roughness Measurement (From Reference 3)

Roughness Increases With Time

In addition to daily roughness variation, pavements generally become rougher with age. Figure 17 shows the profile traces obtained in one of the early Caltrans studies on this matter[6]. As shown, there is a significant increase in profile index within the first year. South Dakota recently reported concerns regarding this issue[12]. They reported a change in roughness within a short interval, perhaps one to three months.

Most specifications do not require a specific time period for profile measurement and/or retests. Since most testing is conducted the following day to enable the contractor to affect change to his paving operation, this most likely would be a problem for retests conducted at a later date. It could also pose a problem if one set of measurements, such as a contractors own measurements for quality control, are used for construction control and another set is used for project acceptance after the paving has been completed. The practical significance of this is not known at this time. However, the structural design of the pavement, concrete mix design, and contractor equipment and placement procedures may no doubt affect the rate of increase in roughness with time.

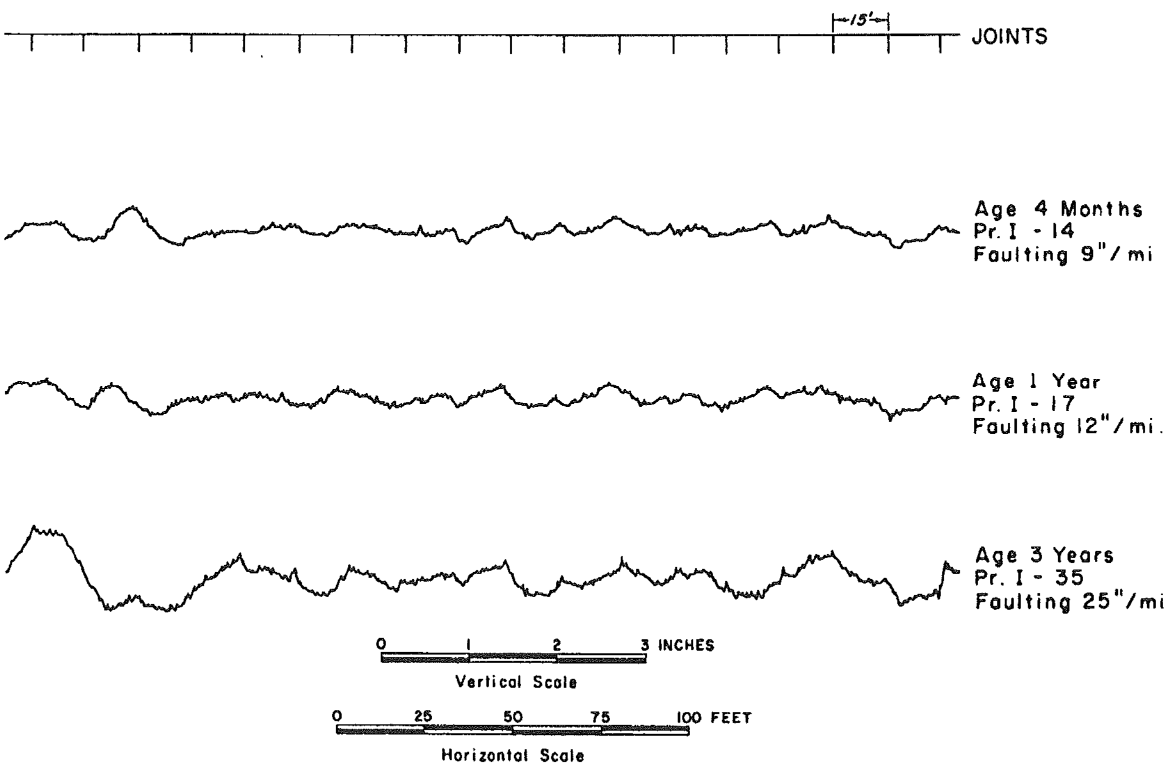


Figure 17 Change in Pavement Roughness With Time (From Reference 3)

Equipment Variability

As previously discussed, there have been several manufacturers of California "style" profilographs over the years. The effect of the different types, if any, has not been reported. Differences in equipment calibration and operating condition between devices of similar manufacture can be large however. As shown in the discussions on tire eccentricity, improper calibration of a device can dramatically change the profile index results.

A study conducted by PTI which evaluated both mechanical and automated devices at three site locations reported that the coefficient of variation ranged from 2.5% to 16.5% with an average of 10.4% for all sites[1]. When the manual trace reductions were removed from the analysis, PTI reported the coefficient of variation at 9.2%. PTI further reported that when five persons manually reduced the traces for one selected site a coefficient of variation of 12.2% was determined between operators.

Operator Variability

Operator variability can affect roughness readings in two ways. First, by the manner in which the testing is conducted. That is roughness readings are affected by the operators ability to ensure the equipment is calibrated properly and the testing conducted properly.

The second manner in which the operator affects roughness readings is during trace reductions. PTI reported that the variations between operators in trace reductions were the same size as total variations of multiple runs with one person reducing the data[1]. Subsequent sections in this report will further discuss experimental findings regarding trace reduction variability.

Aside from the differences in judgement among human beings, one factor which potentially has a significant effect on roughness readings is whether trace outlining is performed. It appears that consistent procedures are required to ensure that all operators do outlining. A difference of one inch of roughness has been reported between trace reduction performed with and without outlining[14].

During the study conducted for this report, operator variability between operators and among operators was evaluated. Results of this work are described in subsequent sections.

Spatial Variability

Most states require profile traces to be obtained in the wheel paths of each lane. Thirty six inches from the lane stripe is often considered the wheel path location. Typically, the profile indexes obtained for the two wheel paths are averaged and reported as the lane profile index for the test section. Some states, however, measure only the center of the lane.

Pavement surfaces vary in roughness in both the transverse and longitudinal directions. This spatial variability makes assessment of the "representative" surface profile difficult for even perfectly accurate measuring devices. Unfortunately, statistical sampling has not occurred in the industry to date. Agencies generally obtain one measurement per wheel path.

Profile index differences as great as 300% (2-4 inches/mile) have been observed between adjacent wheel paths paved in the same operation. It is believed that significant differences exist between wheel paths and lanes on most projects. This confounds the problem of accurate assessment of ride quality. First, by introducing error when the operator tracks improperly or the support wheels track in different paths, and secondly by making assessment of the "subjective ride quality" a problem for statistical analysis and not relying exclusively on averages.

Direction of Travel

Test methods typically do not specify the direction of travel when obtaining profilograph measurements. As discussed previously, the original California specifications were developed based on test results obtained in the direction of travel (traffic). No information has been discovered which describes a bias to the direction of travel.

It is common for manually operated profilographs to be operated in a loop so that the operator is always testing in one direction or the other. This is an expediency necessary to allow timely testing of pavements. Specifications which require all testing to be conducted in the direction of travel would significantly increase test time due to the "deadheading" which would be necessary.

With the introduction of automated devices which utilize signal filtering, serious consideration should be given to determining whether accurate assessments of ride quality are obtained by these devices when operated with and against the direction of traffic.

VII LEGAL ISSUES WITH INCENTIVE/DISINCENTIVE SPECIFICATIONS

Utilization of incentive/disincentive payments is primarily based upon meeting the five following conditions:[16]

(1) "The specification must be incidental to the contract work. That is, the payment cannot be for extra work for which the contractor is allowed to chose whether he wants to perform this work."

(2) "The incentive/disincentive must not be material in comparison to the contract item. In many cases this is considered to be 5% or less of the bid item amount."

(3) "The tests must measure something that the contractor produces by additional skill, care or quality control. The measurement should not be a matter of luck."

(4) "There must be a clear and identifiable benefit to the agency which exceeds in value the amount to be paid or withheld from the contractor under the incentive / disincentive payment schedule."

(5) "The formula for compensation must be clear and known to all bidders in advance."

VIII EXPERIMENTAL STUDY

Introduction

The California Department of Highways developed the profilograph test equipment and roughness specifications to provide an objective method for ensuring a minimum ride quality for concrete pavements. These devices and methods, developed over thirty years ago, were based on subjective ride rating surveys and prepared for convenient and expedient application in the construction environment.

Today, ride quality specifications have been extended far beyond the intent of the original procedures and specifications. In the past, the 7 inch/mile roadway simply represented the minimum ride quality needed. Incentives and disincentives were not used. Incentives today can reach 5% of the bid item unit price. In at least one state the incentive can reach 7%-8% of the unit bid price.

When incentives reach these values they may significantly affect contractors' bid procedures since this level approaches their profit margins. It is no wonder that increased concern/interest in profilograph testing and reporting is occurring. With such incentives available and improvements in paving equipment and concrete mix design, contractors are capable of producing pavements with roughness levels in the 2 to 5 inch/mile range.

Although the California profilograph and roughness specifications have served the industry well over the past thirty to fifty years, two questions need to be resolved. First, is the test procedure and equipment sufficiently accurate and reproducible to warrant such significant incentive/disincentive specifications and secondly, does the 7 inch/mile "bench mark" typically found in specifications represent the proper value for today's vehicles, drivers, and construction techniques?

Because of these questions and the need to evaluate the performance of the automated profilograph, a statistical study was conducted. The objectives of this study were to:

- Develop precision and bias statements for the California profilograph.
- Compare mechanical and automated profilograph test results.
- Evaluate equipment variability.
- Evaluate operator variability in equipment operation and trace reduction.
- Determine if pavement roughness changes during profilograph testing.
- Evaluate the effects of data filter settings on profile index readings.
- Determine the effect of direction of travel on test results.

Experimental Design

To accomplish these objectives three test plans were developed; one to develop a precision and bias statement for profilograph testing, one to determine operator variability in trace reduction, and one for analyzing the effect of the data filter settings.

Precision and Bias Experiment (Main Experiment)

The main experiment was designed to develop a precision and bias statement for profilograph testing. To accomplish this it was recognized that "actual roughness" values would have to be determined to provide a bench mark by which to compare the profilographs. This required conducting the experiment in two phases. Phase I, which is reported herein, consisted of the field work and statistical analysis of the profilograph test results. Phase II will consist of developing a precision and bias statement for the profilograph with the data obtained with a KJ Law 690DNC profilometer as the reference comparison.

The main experiment was conducted by utilizing a 4x4x2 randomized block design with replication, resulting in a total of 64 profilograph runs. The experimental design consisted of two levels of roughness, (2.5 and 10 inches/mile), 4 operators, and 4 profilographs (two mechanical and two automated).

Trace Reduction Variability Experiment

The trace reduction experiment consisted of a 4x2x2 randomized block design with replication. The experimental design consisted of four operators, two mechanical devices, and two levels of roughness (2.5 and 10 inches/mile). Eight traces were analyzed by each of the four operators.

Data Filter Setting Experiment

The data filter setting experiment consisted of a 3x2x2x2 randomized block design with replication. The experimental design consisted of three data filter settings (8000,6000,4000), two automated devices, two operators, and two roughness levels (2.5 and 10 inches/mile). A total of 48 runs were conducted.

Test Site Location

The field testing was conducted in Phoenix, Arizona between September and November 1990. Testing was performed upon an undoweled plain jointed concrete pavement 12 inches in thickness. The concrete pavement was constructed on an aggregate base and utilized skewed random joint spacings of 13,15,17,15 feet. The pavement had been constructed approximately five months earlier and had only incurred construction traffic. The construction project and study area were not open to the public.

Initially three levels of roughness were desired to better represent the range of expected roughness levels obtained during construction operations. However, the large number of tests needed for this experiment and the difficulty in finding test sections in close proximity for convenient testing resulted in only two levels of roughness selected.

Over 160, one-tenth mile long sections were reviewed for roughness values. The selected one-tenth mile long section had an average reported roughness value of 6.3 inches/mile with the left wheel path measuring 2.5 inches/mile and the right measuring 10.0 inches/mile. This proved to be the ideal site because it enabled two levels of roughness to be tested within a single one-tenth mile long section. The selected segment also met an additional criteria used in site selection: no grinding within the test area. Since the pavement had previously been constructed, acceptance testing and grinding had been performed on some areas. The criteria for an unground pavement section resulted from the need to best represent the wavelengths produced by slip form construction and not those produced from grinding.

The test section location is shown in Figure 18. The outer lane of the northbound roadway was used for the test section. The outer wheel path represented the rough section and the inner wheel path the smooth section. The roughness "rankings" were established from the construction acceptance test records.

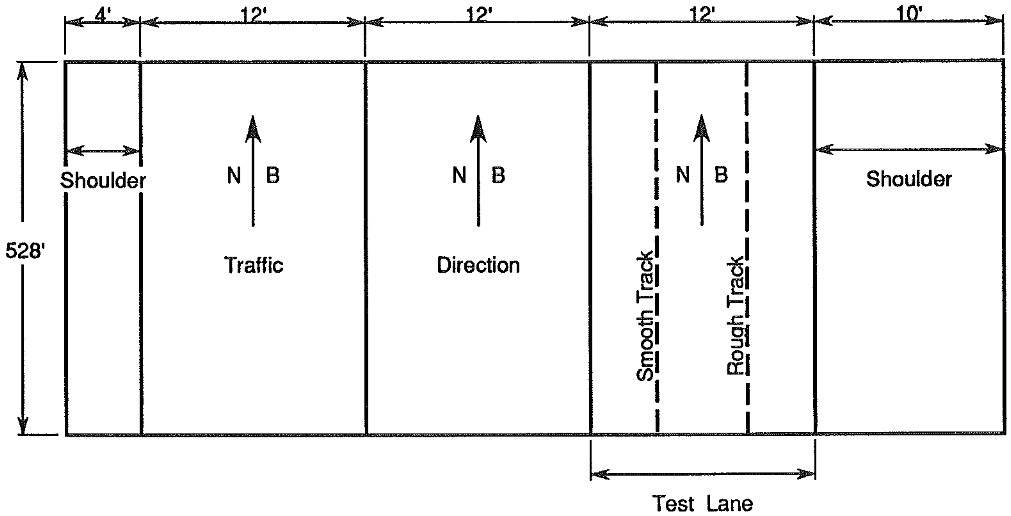


Figure 18 Test Section Location – SR101 @ MP. 15.4 (Construction Station 846+50 – 851+78)

Equipment and Operators

The participating agency provided four profilographs, two mechanical and two automated. The automated devices were Cox and Sons, Inc. Model CS8200. One was a retrofitted McCracken unit and one was an original CS8200 unit. Although not verified, the two mechanical units were believed to be Cox devices. The age of the units ranged from 24 years to 1 year. For test purposes the two mechanical devices were identified as M1 and M2, while the two computerized devices were identified as E3 and E4.

The operators used for these experiments represented actual construction operators. Each operator represented a different construction group. Therefore any differences in methods or procedures between construction groups would be revealed in the variability of their readings.

The four operators used in the field testing were not the same as those used for the trace reduction analysis portion. Problems with personnel availability precluded consistent use of all operators between these two segments of the experiment.

Test Procedures

Precision and Bias Experiment

The purpose of the main experiment was to determine the "actual" field variability as opposed to the "ideal" variability possible with the devices. Therefore the operators were not instructed on how to conduct the testing. They were only instructed on the run sequences and the manner in which the operators would switch devices to provide randomization. Each operator delivered the device managed by their construction unit to the test location. The operators assembled their own devices in their normal manner. Prior to conducting testing, the research group checked each device after assembly for proper calibration. One inch calibration blocks were used for checking the vertical calibration for the manual units and all units were gaged against a pre-surveyed 528 ft. distance calibration check. Each of the measurement wheels were visually checked for eccentricity. It took three separate attempts to accomplish the complete experiment with all devices in satisfactory operating condition. Although the final testing was completed in an 8 hr. period, it took several months to arrange the logistics for mobilizing all four units and operators during the three attempts at conducting the experiment.

Prior to assembling the profilograph units a KJ Law 690DNC profilometer was used to conduct the first series of runs over the test sections. A total of ten runs were made with the profilometer during the day, representing the time span over which the main experiment was conducted. This provided the ability to evaluate any changes in actual pavement roughness with time of day (i.e. thermal curling). Five runs were made with the profilometer for each of the two test sequences. One test sequence was conducted in the morning and one in the afternoon. Since the profilometer measures the profile in each wheel path simultaneously, only one run was necessary to obtain both wheel paths. The Mays statistic was used to evaluate field test results during the field portion of the experiment. Because three attempts were necessary to accomplish the entire experiment, profilometer data was obtained for three different days over a period of three months. Although unplanned, this allowed evaluation of the changes in pavement roughness with time.

Profilograph testing was conducted in two replicates and in a complete randomized block design as much as possible within each replicate. Complete randomization was limited by two operators and two machines testing at relatively the same time. This allowed continuous testing with all operators and devices while ensuring statistical validity. Testing began in the rough track in the direction of travel. Upon completion of this run, a new order of machines and operators was established in accordance with the prescribed plan. Testing was then commenced in the smooth track in the opposite direction of traffic. This "looping" allowed testing to be conducted without the need for deadheading the equipment. During testing no guides were used to ensure proper tracking, only visual alignment was used.

Trace reduction for the mechanical devices was accomplished using only one individual. This minimized trace reduction variability. One of the authors performed all trace reductions to provide as consistent evaluations as possible.

Data Filter Setting Experiment

Upon completion of the main experiment, the data filter experiment was conducted using two operators and two automated profilographs. As in the main experiment, run sequencing was conducted in a randomized complete block design within replicates, subject to the testing performed in pairs. This allowed continuous testing with both operators and devices. Again only visual alignment control was used.

Trace Reduction Variability Experiment

Profilograph traces produced with each of the mechanical devices M1 and M2 during the first attempt at the main experiment were used in the trace reduction variability experiment. Operators were not instructed regarding trace reduction techniques. They used their own established procedures.

Four operators were each given the same eight sets of profilograph data to interpret. The eight sets consisted of four runs on the smooth track and four runs on the rough track. For each condition, two runs were done by M1 and two runs by M2. The eight graphs were labelled in random order and given to each operator. After the first trace reductions were completed, a new random order of the same traces were sent to the same operators for reduction.

Approximately one month of time transpired between reductions. At the time of the first reduction, the operators were not advised regarding the second set of readings.

All photo copies of the traces were obtained from the same originals by a xerox 2080 machine. This machine was selected to alleviate the concern that the final traces would exhibit distortion when compared to the original traces. This also allowed production of clean unmarked profiles for each reduction. This precluded any bias which might result from eraser marks on the traces during operator interpretation.

Analysis Procedures

Four main categories of statistical procedures were applied during data analysis: (a) F-test factorial analysis of variance ; (b) Student T-test for comparison of two means; (c) Duncan's Multiple Range Tests for multiple comparison of several means; and (d) Statistical Process Control (SPC) for the analysis of response repeatability and reproducibility. The F-test was employed to test the significance of treatment effects. The F-test was also used to determine the significance of factor effects and the presence of interactions in factorial analysis of variance. The Student T-test was employed in cases that involved the comparison of two means. Where the desire was to make multiple comparisons of several means, Duncan's Multiple Range test was used.

Repeatability can be defined as the ability of a process to produce the same response when the process is replicated. Reproducibility refers to the ability of the process to produce the same response when the process is repeated under varied treatment combinations. Repeatability and reproducibility provide a quantitative measure for data dispersion. To measure repeatability or reproducibility, first, process control specifications (Upper Control Limits and Lower Control Limits) are determined. Second, the percent of the total responses that fall within the specified Lower and Upper Control Limits are obtained.

IX EXPERIMENTAL RESULTS

As previously discussed this testing represents only Phase 1 of the experiment. These results evaluate test variability. A precision and bias statement cannot be obtained until Phase II when the "true" roughness is established with the use of the profilometer data and a computer simulation of a profilograph. It should also be noted that the variabilities discussed herein represent construction quality control variability and not necessarily the optimum variability achievable. Although, they may indeed be the same.

Three forms of measurement description are used in this report. The first is accuracy. This term defines how well a test value represents the true value of roughness. Accuracy of test results will not be discussed until Phase II of the experiment. The second is repeatability. This term defines how well a particular device or operator can duplicate roughness results when the test is repeated. The third term is reproducibility. This term refers to how well any device or operator can be expected to compare to other operators or devices.

The mean roughness values obtained from all testing was 5.3 inches/mile and 9.0 inches/mile for the smooth and rough tracks, respectively. Although this range is not consistent with the roughness values used for site selection, they represent values typically found in the incentive range (<7 inches/mile) and in the grinding range (>9 inches/mile).

Equipment Variability

The analysis of variance conducted for this study indicated that:

- Profile Indexes produced by the four devices were statistically different at the 1% significance level.
- Different operators produced statistically different Profile Indexes at a significance level of 7%.*

* This does not consider operator variability due to trace reduction.

Variability Between Devices

In general, the two mechanical devices exhibited slightly better repeatability than the automated devices. That is, for a given combination of operator and device, the mechanical systems provided slightly more consistent results. Table 2 indicates the repeatability of each device for both the smooth and rough tracks. All devices were repeatable within two inches/mile on the rough track and within 1.5 inches/mile on the smooth track.

A single individual analyzed the profile traces for the mechanical devices. This minimized the effect of trace reduction variability on the results from mechanical devices.

The average repeatability was worse for the rough road (0.75 inches/mile) than for the smooth road (0.56 inches/mile). This repeatability represents the average repeatability of four operators for each device. The average repeatability of four operators provides a better estimate of actual repeatability.

Figures 19 and 20 represent the percent of test results within a specified tolerance range about the mean for each device in graphical form for both the smooth and rough tracks, respectively. For example, approximately 100% of the test results obtained by all four operators for device E4 were within one inch/mile of the mean value for that device for the smooth track condition. However, only about 60% of the test restuls were within one inch/mile of the mean for device E4 for the rough track condition.

TABLE 2 DEVICE REPEATABILITY GIVEN IN PERCENT OF TOTAL READINGS WITHIN A SPECIFIED RANGE ABOUT THE DEVICE MEAN

	PAVEMENT SURFACE CONDITION					
DEVICE	SMOOTH			ROUGH		
ID	0.5"	1"	2"	0.5"	1"	2"
M1	75	100	100	25	75	100
M2	75	100	100	75	100	100
E3	50	75	100	75	100	100
E4	75	100	100	50	50	100

The range of roughness readings obtained during testing is shown in Figure 21. The solid bars shown in this figure indicate the range of roughness values obtained for all operators with each of the devices for both the smooth and rough conditions. The mean values for both the smooth and rough conditions are designated by the vertical lines. This visual display of variability indicates that even though individual devices may be very repeatable, they may indeed arrive at different answers than other devices with equal repeatability. The variability of the test devices, estimated by six standard deviations, ranged from 3 inches/mile for device M2 to 5.4 inches/mile for device E4.

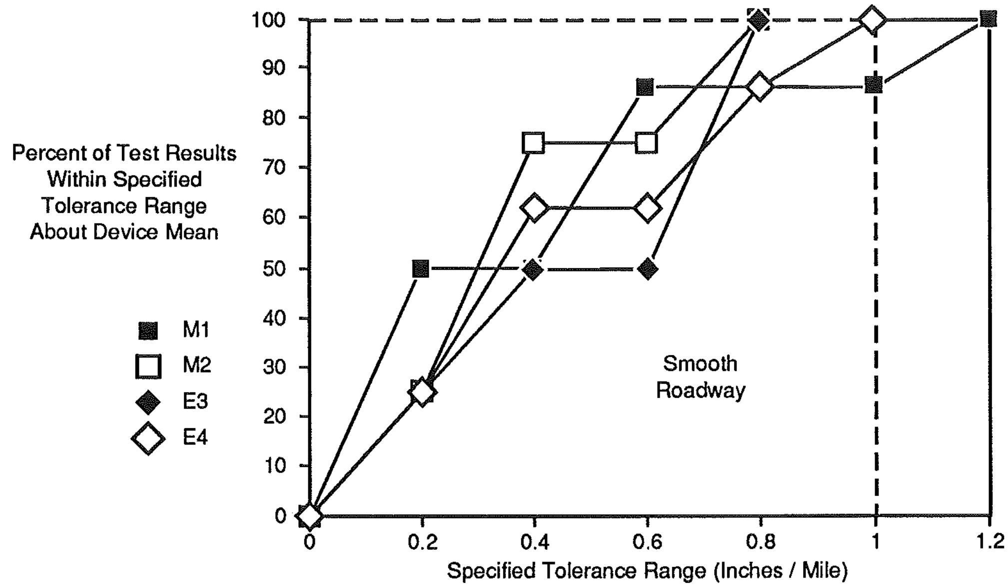


Figure 19 Repeatability of Roughness Measurement For Each Device For Smooth Track Condition

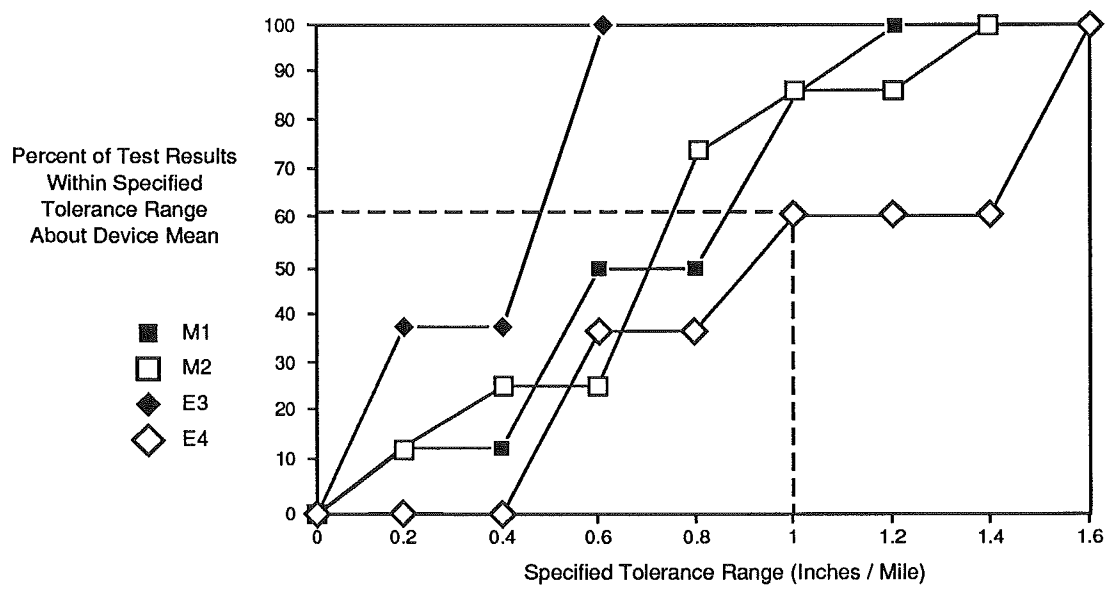


Figure 20 Repeatability of Roughness Measurement For Each Device For Rough Track Condition

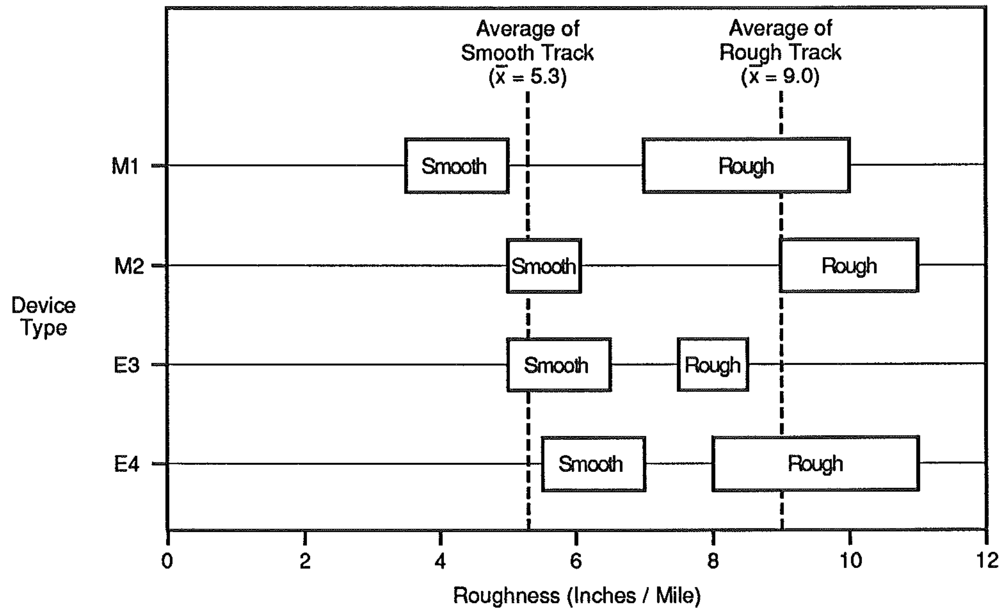


Figure 21 Range of Roughness Readings Obtained During Testing

Table 3 indicates the descriptive statistics for each of the devices. The coefficient of variation ranged from 5.2% to 13.2% for the individual track readings. The average coefficient of variation was 10.4% for the mechanical devices and 9.1% for the electronic devices. The lower average coefficient of variation for the electronic devices should not be construed as meaning it has less variability. Previously, it was stated that the mechanical devices were slightly more repeatable. The reason for the percieved lower variability, as described by the coefficient of variation, is due to the higher mean of the electronic devices (i.e. $\bar{x}$=7.5 for electronic and $\bar{x}$=6.9 for mechanical) and the computation of the coefficient of variation (i.e. C.V.=$\sigma/\bar{x}$). This effect is also evident when comparing reported coefficients of variaiton from other studies such as the PTI report which indicated slightly lower variability (i.e. C.V.=9.2%).[1] However, the average profile index on the three sites evaluated in the PTI study ranged from 39 to 67 inches / mile. This level of roughness is significantly beyond the level of roughness encountered in new construction.

TABLE 3 DESCRIPTIVE STATISTICS FOR DEVICE REPRODUCIBILITY

Reproducibility for Mechanical Devices

DEVICE ID	M1				M2			
STATISTIC	$\bar{X}$	STD	C.V.	R	$\bar{X}$	STD	C.V.	R
BOTH PATHS	5.94	2.25	37.9	6.50	7.98	2.66	33.3	6.00
SMOOTH PATH	3.94	0.50	12.6	2.00	5.38	0.44	8.2	1.00
ROUGH PATH	7.94	1.05	13.2	3.00	10.36	0.79	7.6	2.00

Reproducibility for Electronic Devices

DEVICE ID	E3				E4			
STATISTIC	$\bar{X}$	STD	C.V.	R	$\bar{X}$	STD	C.V.	R
BOTH PATHS	6.91	1.29	18.7	3.5	7.91	1.86	23.6	5.50
SMOOTH PATH	5.75	0.60	10.4	1.00	6.31	0.53	8.4	2.00
ROUGH PATH	8.06	0.42	5.2	1.00	9.50	1.17	12.3	3.00

Figure 22 is a plot of the coefficient of variation as a function of pavement roughness. The plot includes the data from the main experiment as well as the PTI study previously discussed and additional data obtained in Arizona on Interstate 40. Unfortunately, these coefficients are not directly comparable. The variation shown for the I-40 testing was for one machine with two operators. The PTI study used one machine with one operator. The data for the main experiment is for four devices with four operators. Ignoring this shortcoming, it is evident that most of the variability was between 5% and 15%. Looking only at the Arizona data, it appears that a correlation does not exist between pavement roughness and the coefficient of variation of profilograph test results. The R^2 for this regression was 0.2. The Arizona data "suggests" that as the pavement roughness decreases the coefficient of variation increases. When a profilograph attempts to measure a very smooth pavement, its variability may begin to approximate its own resolution of accuracy and not necessarily the condition of the surface. No data has been obtained which can validate this assumption, however.

A study conducted by ARE Inc. performed 72 profilograph runs in a designed experiment to evaluate roughness of AC pavements.[17] This experiment consisted of evaluating four levels of roughness with three test sections within each roughness level. Three runs were performed for each test section with replication for all testing. Two operators were used to conduct the testing. Although the wavelengths present in an AC pavement are presumably different than in a concrete pavement, it is interesting to note the increase in coefficient of variation as measured pavement roughness decreases as shown in Figure 23. The R^2 for this regression was 0.43. Again as in Figure 22, this correlation is not strong. However, it further supports the hypothesis that the coefficient of variation increases as roughness decreases. The ARE study concluded that the median and 90th percentile coefficients of variation were 9.5% and 21.7%, respectively

Variability Due to Direction of Travel

A supplemental experiment was performed to evaluate whether the direction of travel during testing affected the readings. With the new automated devices concern existed regarding whether the low band filters were sensitive to direction of travel. Due to field problems, data was only replicated for one direction. The data which was replicated was averaged and then the two directions compared. The results of this study indicated that none of the four devices were directional. Table 4 presents the descriptive statistics for the test results.

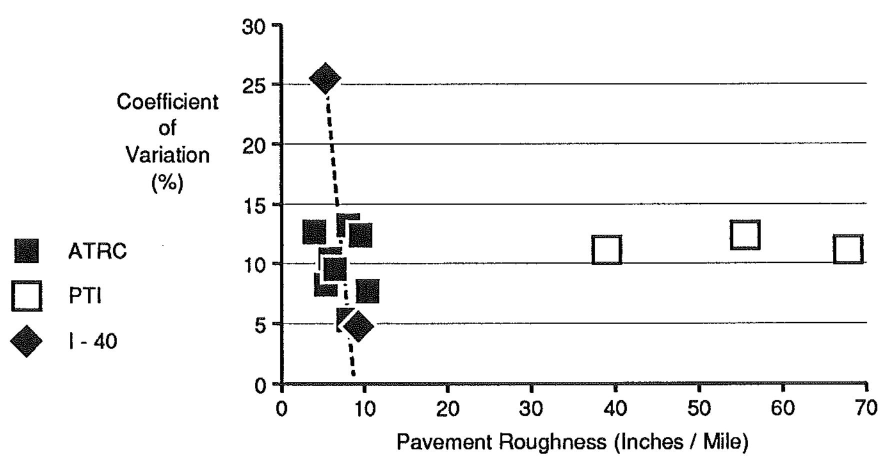


Figure 22 Effect of Roughness on the Coefficient of Variation of Profilograph Results For Concrete Pavements

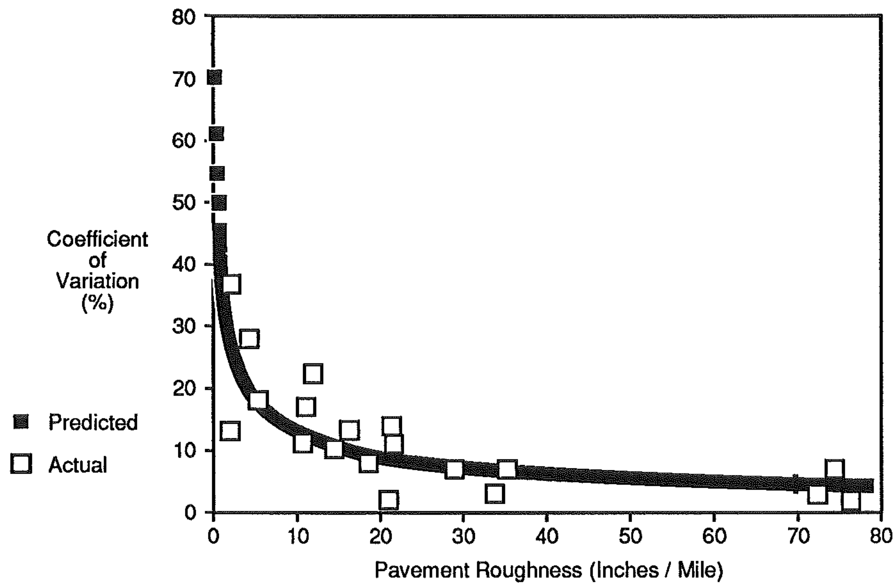


Figure 23 Effect of Roughness on the Coefficient of Variation of Profilograph Results For Asphalt Concrete Pavements

TABLE 4 DESCRIPTIVE STATISTICS FOR DIRECTION OF TRAVEL TEST RESULTS

DEVICE ID	M1			M2			E3			E4		
PARAMETER	$\bar{X}$	STD	C.V.	$\bar{X}$	STD	C.V.	$\bar{X}$	STD	C.V.	$\bar{X}$	STD	C.V.
WITH TRAFFIC	6.1	3.9	63.7	8.6	6.0	70.1	8.3	3.6	43.0	6.7	3.7	55.6
AGAINST TRAFFIC	6.1	3.6	59.4	8.5	3.8	44.2	8.5	4.0	47.3	6.5	2.5	38.2

Variability Due To Data Filter Settings

The Cox and Sons Model CS8200 recommends a data filter setting of 8000. To evaluate the effect of reducing this filter setting, two operators and two automated devices were evaluated at three settings for both the rough and smooth conditions. A total of 48 runs were performed. The results of this testing are presented in Figure 24. The solid lines represent both the smooth and rough track results. Surprisingly, combining both the smooth and rough track conditions results in an almost perfect linear relationship as shown by the dashed line.

As can be seen in Figure 24, at a data filter setting of 4000 there is approximately a 30% reduction in the profile index which would be obtained with the setting at 8000. A reduction of approximately 7% of the 8000 setting value occurs for every 1000 unit change in the data filter setting. The three values represented in Figure 24 constitute the average of all values obtained at a given filter setting.

An analysis of variance was performed on the data at a significance level of 1%. The results indicated that the filter setting had a significant effect on the roughness value. Duncan's multiple range test confirmed that each setting was distinct at a 1% significance level. The analysis of variance also indicated significant interactions between operators and road roughness, and operator and devices.

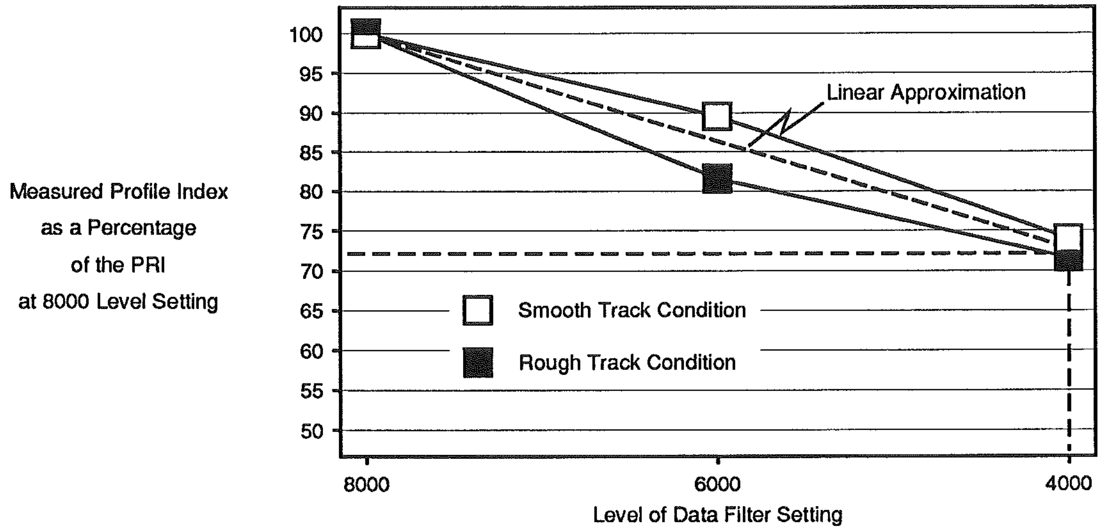


Figure 24 Effect of Data Filter Setting on Profile Index

The difference in average readings between operators was 0.61 inches/mile while the average difference between devices was 0.65 inches/mile. The difference due to filter setting was almost one inch between each setting level (i.e. 8000= 7.4 inches / mile, 6000= 6.4 inches / mile, 4000= 5.3 inches / mile). Table 5 presents the descriptive statistics for this testing.

TABLE 5 DESCRIPTIVE STATISTICS FOR DATA FILTER SETTINGS

SETTING	8000			6000			4000		
PARAMETER	$\bar{X}$	STD	C.V.	$\bar{X}$	STD	C.V.	$\bar{X}$	STD	C.V.
PRI VALUE	7.38	2.33	31.57	6.38	2.19	34.33	5.34	1.81	33.9
% OF 8K	100	–	–	86.5	–	–	72.4	–	–

One of the problems associated with attempting to determine specific effects from these settings is the strong interactions of the co-factors such as road roughness and device. For example, although the operators got nearly the same average value on the smooth sections, their average values differed by more than one inch / mile for the rough condition. Similarly, while the two operators obtained almost the same average readings on device E4, their average readings for device E3 differed by more than 1.5 inches / mile.

Operator Variability

Operator variability consists of both field variability and trace reduction variability. Field variability is a result of the operators inability to traverse the same path each time, measure the exact path location, and test at the same speed. It also is affected by test procedures and equipment calibration. The trace reduction variability is an additional variability produced by the operator with mechanical devices. Once an operator obtains a profile trace from a mechanical device it must be manually interpreted. This allows considerable judgement to be exercised in the trace analysis. An example of such a judgement factor would be whether the individual performs "outlining " prior to evaluating the trace.

Trace Reduction Variability

Since the true measure for each roughness condition was unknown, an accuracy interpretation could not be performed. However, all readings for the smooth condition were within three standard deviations of the mean (i.e. $\overline{x}$=3.78 inches/mile). For the rough condition, one reading (i.e. 16 inches/mile) was out of control or outside of the three standard deviation interval for the mean of 8.58 inches/mile (i.e. 2.07 to 15.09). It should be noted that other than the extreme lack of repeatability by operator 2 on one run where the readings were 9.5 and 16 inches/mile for a difference of 6.5 inches /mile, operator 2 was the most consistent of the operators. His range was 1.0 inch/mile for the other sets of data. The actual calculations by operator 2 were rechecked and verified against a possible error in calculation or in recording. The extreme of 16 is worthy of concern in that it shows the present system is not adequate to prevent an out of control point, even by an excellent operator.

Sixty seven percent of the total operator trace reduction variability was due to the difference between the operators and the repeated readings. There was more variability between the average values among operators than there was variability between the two readings of a single operator.

Operator trace reduction repeatability was determined by conducting a paired t-test of the first and second trace reductions by individual operators. All four operators analyzed the same eight traces. The eight trace reductions represented two runs (i.e. replicate runs) by each of the devices M1 and M2 for both the rough and smooth track conditions. Since the replicate runs include field variability due to test and equipment variability, the traces produced by these runs were not compared for repeatability determination. Instead, the trace produced by an individual run, which was provided to the operator on two occasions, was evaluated. The operator repeatability was evaluated in terms of the operator's ability to interpret the same trace again. Table 6 presents the descriptive statistics for this analysis. The results of the analysis indicated that, at a significance level of 5%, no statistical difference was found between an operators first interpretation and his second.

Figure 25 represents the average repeatability for trace reduction for the operators. As evident, trace interpretation was more repeatable for the smooth track condition than for the rough track condition. Figures 26 and 27 represent the average operator repeatability for each device and roadway condition. It should be noted that for the smooth track condition (Fig 26) the average repeatability for both devices was the same. For the rough track condition (Figure 27) the repeatability was considerably different between the devices. Figure 28 represents the average repeatability by operator for both the rough and smooth track results combined.

It should be emphasized that the previous discussions indicated that the four operators produced statistically similar repeatability for trace interpretation. However, their results were statistically different. An example of how this happens can be seen in Figure 29. This figure represents the range for all values produced by a given operator, on a given machine, and a given test track. The solid bar represents the range obtained by a given device traversing a specified path twice. Each of two traces produced by these runs were then interpreted twice by the same reader.

The repeatability seemed to depend more on the machine source. Each machine was the source of profiles that were read with a range of 4" or more in two readings. However, the data from M1 did appear to be read with better repeatability than M2. Fifteen of the 16 sets of data from M1 had a range of at most 2 inches / mile. Only 12 of the 16 sets of readings from M2 had a range of at most 2 inches/mile. The average repeatability of the operators' results was 0.94 inches/mile for M1 and 1.72 inches/mile for M2. Profile traces from M1 and M2 are shown in the top and bottom of Figure 15, respectively. It should be noted that the trace from M2 has significantly more "noise". Since outlining was not performed, this could explain some of the large differences. The standard deviation of the ranges was 0.99 inches/ mile for M1 and 1.52 inches/mile for M2.

Trace reduction reproducibility among operators was determined by performing an analysis of variance on the roughness values determined by each operator. The results of this analysis conducted at a significance level of 5% indicated that the operators produced statistically different results. As evident in Table 7, the overall mean values ranged from 4.9 to 7.6 inches/mile and the coefficients of variation for the smooth and rough road ways ranged between 14.7% and 38.3%.

TABLE 6 DESCRIPTIVE STATISTICS FOR TRACE REDUCTION REPEATABILITY

		SMOOTH TRACK VALUES (IN/MILE)					ROUGH TRACK VALUES (IN/MILE)				
		DEVICE M1		DEVICE M2			DEVICE M1		DEVICE M2		
		TRACE NO.		TRACE NO.		**MEAN**	TRACE NO.		TRACE NO.		**MEAN**
OPERATOR	STATISTIC	1	10	2	12		7	13	8	15	
1	Average	4.00	7.00	4.25	7.00	**5.56**	8.00	8.50	10.75	11.50	**9.69**
	Difference	2.00	4.00	2.50	2.00	**2.63**	1.00	1.00	1.50	1.00	**1.13**
2	Average	3.25	4.00	5.50	6.75	**4.88**	7.00	7.75	12.75	11.00	**9.63**
	Difference	0.50	1.00	1.00	0.50	**0.75**	0.00	0.50	6.50	1.00	**2.00**
3	Average	1.75	2.75	2.00	2.75	**2.31**	7.25	6.75	8.50	7.50	**7.50**
	Difference	0.50	0.50	1.00	0.50	**0.63**	0.50	0.50	1.00	3.00	**1.25**
4	Average	1.50	2.75	2.50	2.75	**2.38**	6.75	6.50	8.00	8.75	**7.50**
	Difference	0.00	0.50	1.00	0.50	**0.50**	0.50	2.00	3.00	1.50	**1.75**

Average: Average of two replicate readings
Difference: Absolute difference between two replicate readings
MEAN: Overall average for operator within track

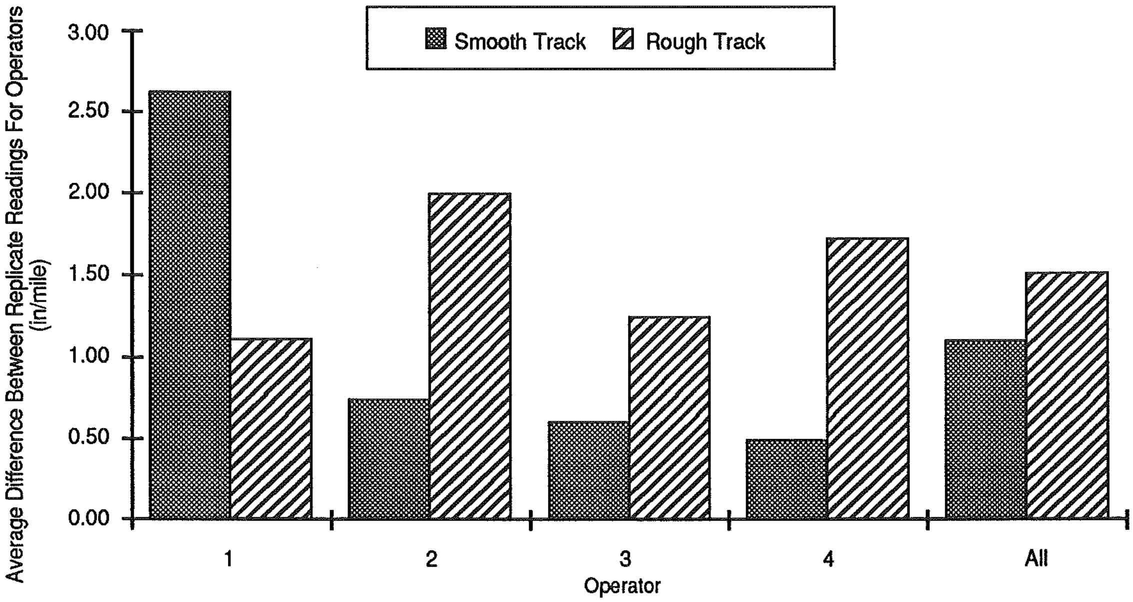


Figure 25 Average Operator Trace Reduction Repeatability

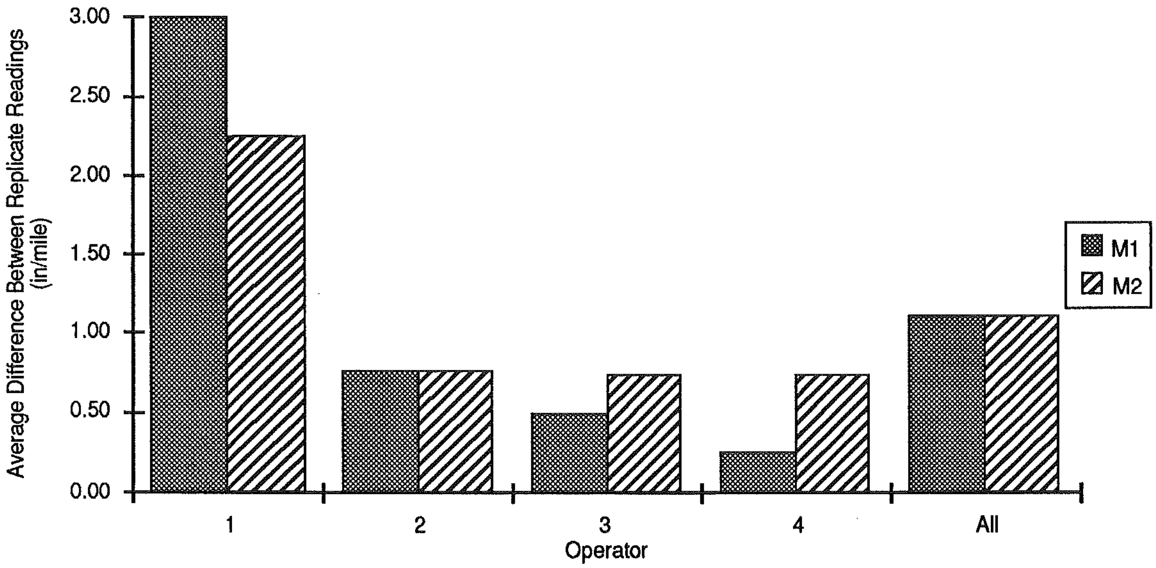


Figure 26 Average Difference of Replicate Readings by Operators For Smooth Track Condition

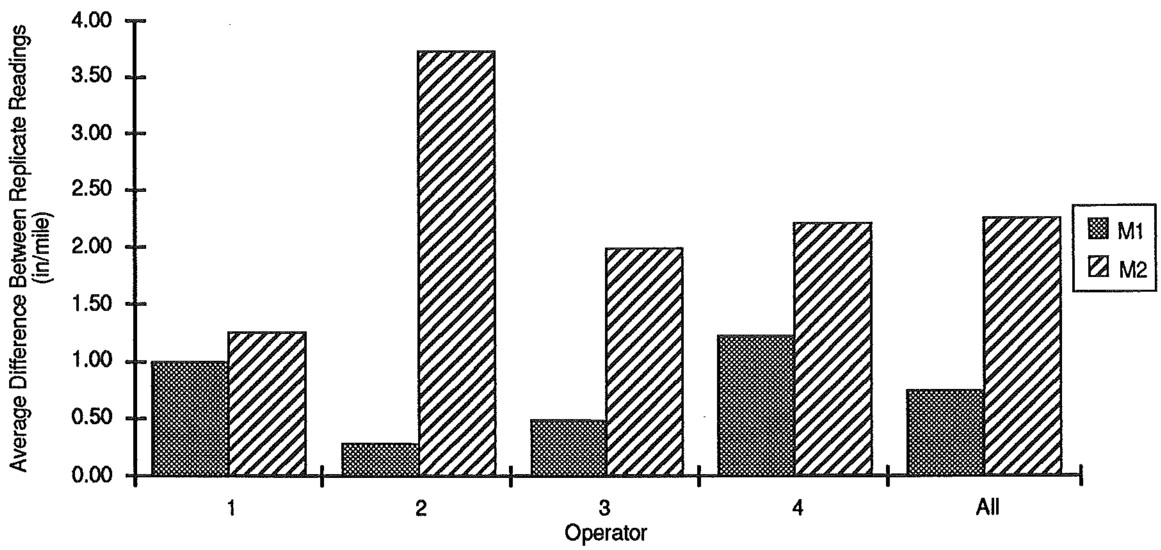


Figure 27 Average Difference of Replicate Readings by Operators For Rough Track Condition

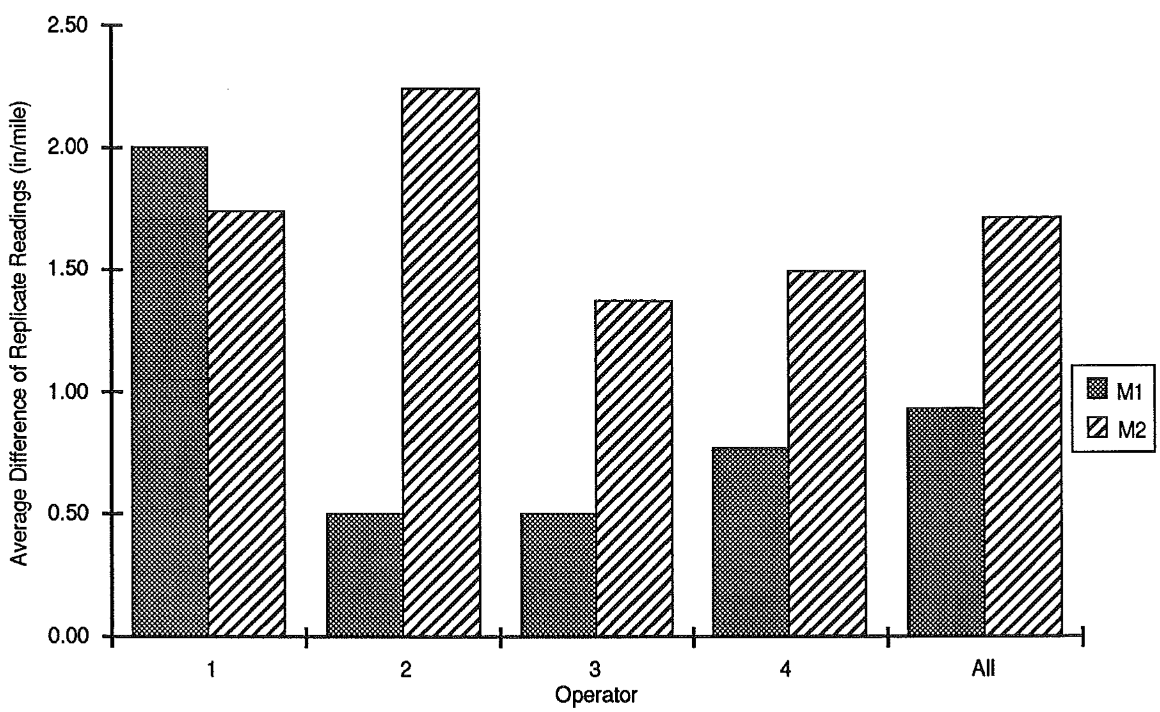


Figure 28 Average Difference of Replicate Readings by Operators For Both Smooth and Rough Track Conditions

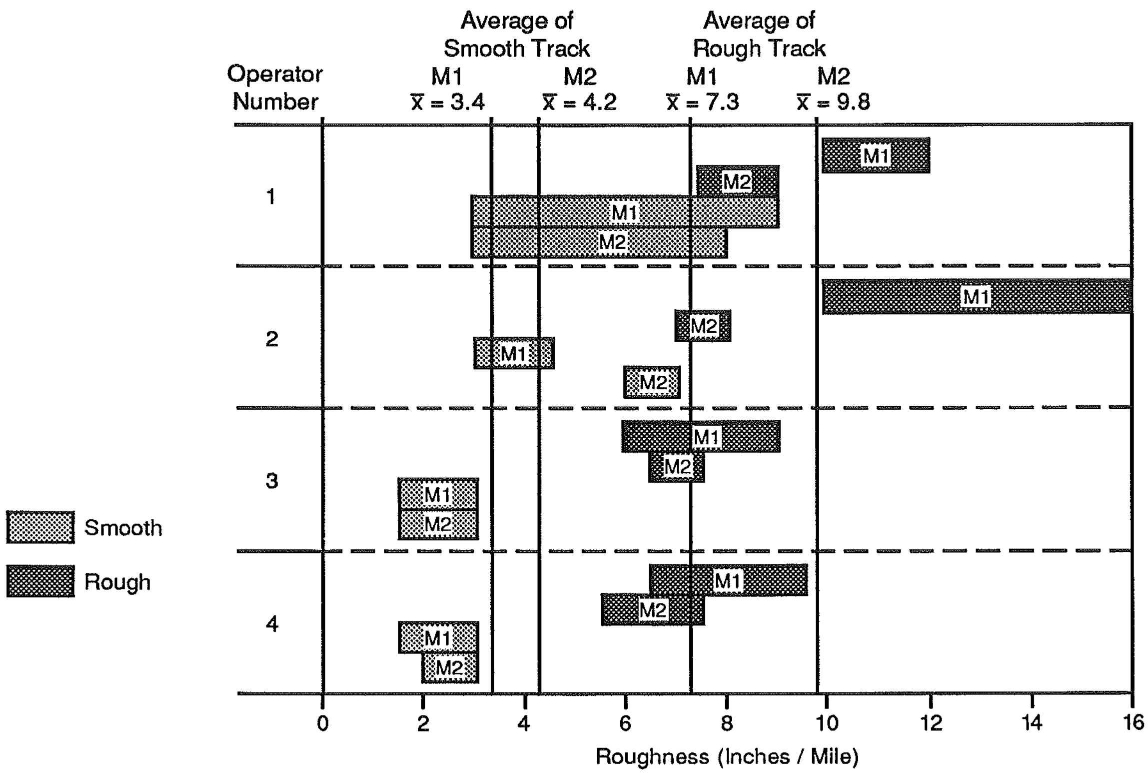


Figure 29 Range In Readings For All Values Produced by a Given Operator, Machine, And Track Condition

TABLE 7 DESCRIPTIVE STATISTICS FOR TRACE REDUCTION REPRODUCIBILITY

OPERATOR ID NUMBER	OVERALL STATISTICS				PAVEMENT SURFACE CONDITION							
					SMOOTH				ROUGH			
	$\bar{X}$	STD	C.V.	R	$\bar{X}$	STD	C.V.	R	$\bar{X}$	STD	C.V.	R
1	7.63	2.83	37.04	9.0	5.56	2.128	38.25	6.0	9.69	1.689	17.43	4.5
2	7.25	3.39	46.70	13.0	4.88	1.506	30.86	4.0	9.63	3.068	31.86	9.0
3	4.91	2.81	57.27	7.5	2.31	0.594	25.68	1.5	7.50	1.102	14.69	3.0
4	4.94	2.86	57.83	8.0	2.38	0.641	26.93	1.5	7.50	1.439	19.19	4.0

Pavement Roughness Variability

Test Variability Resulting From Time of Day

To evaluate changes in roughness due to time of day, a KJ Law 690NDC profilometer was used. Prior to testing with the profilographs, five tests were conducted with the profilometer at a speed of 50 mph. These tests were typically conducted between 7:30 am and 8:30 am on each of the three test days. A second set of five profilometer tests were conducted between 10:00 am and 11:00 am. This corresponded with the latter portions of the main profilograph experiment. This three to four hour window of testing was designed to establish whether the pavement roughness changed during the profilograph testing.

The KJ Law 690DNC is an ASTM Class I profile measurement device. Two profile statistics were utilized in this testing; the Mays roughness index and the International Roughness Index (IRI). Mays units are expressed as inches per mile and represent the response of the vehicle to the effects of both wheel paths. IRI units are also expressed in inches per mile. However, IRI represents the response of the vehicle to the effects of a single wheel path. That is, the IRI unit is computed individually for both the right and left wheel paths. A total IRI can be computed by averaging the values obtained by the right and left wheel paths. The results of this testing are displayed in Table 8 and Figure 30. As shown, the roughness measured by the profilometer indicates a decrease in roughness between morning and afternoon readings of 7% - 10% for the three test dates. The rate of change in roughness was approximately 2-3 inches/mile/hour. The Mays statistic is used for this comparison. Unfortunately, no direct comparison between the Mays units and profile index was established for this study.

TABLE 8 PROFILOMETER GENERATED MAYS AND IRI ROUGHNESS VALUES

		MORNING			AFTERNOON		
		Sep 26	Nov 7	Nov 21	Sep 26	Nov 7	Nov 21
MAYS	MEAN	83.30	89.50	91.50	77.60	80.90	83.30
	STD	3.00	2.90	0.90	1.30	1.50	1.60
	CV	3.60	3.20	1.00	1.70	1.90	2.00
IRI SMOOTH TRACK	MEAN	91.90	97.80	–	84.30	87.70	90.30
	STD	1.50	3.40	–	1.30	2.80	1.70
	CV	1.70	3.50	–	1.60	3.20	1.90
IRI ROUGH TRACK	MEAN	109.30	117.10	–	98.60	102.20	105.60
	STD	5.60	3.50	–	2.50	1.30	1.20
	CV	5.20	3.00	–	2.60	1.20	1.10

During the morning testing with the profilometer, numerous tests included situations termed lost lock and saturation. These conditions can be caused by excessive sunlight entering beneath the shrouds of the test van. This can result in higher than actual readings. The profile traces have not currently been processed for these spikes. Therefore, the reader is cautioned as to the validity of this data. This processing will occur during Phase II of this study and more definitive conclusions obtained at that time.

Analysis of the profilograph data indicated no statistical difference between readings obtained in the morning and those obtained in the afternoon. Presumably, the large variation in profilograph test results masked the small changes in pavement roughness which were measured by the profiliometer.

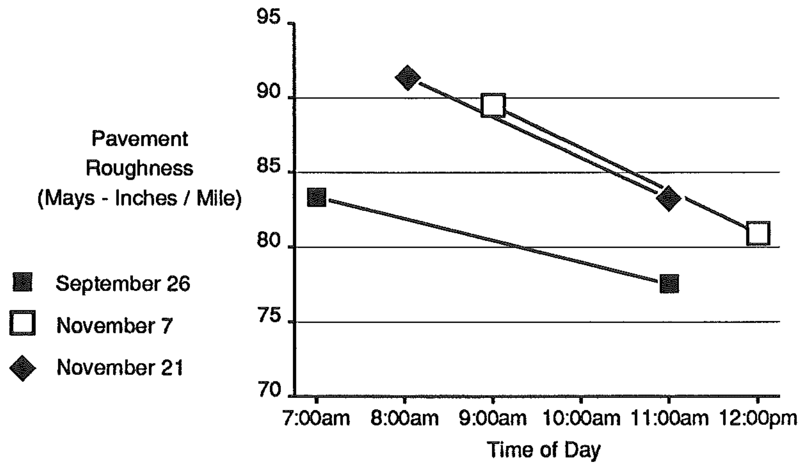


Figure 30 Daily Change in Pavement Roughness

Change in Pavement Roughness With Time

Since the testing was conducted on three separate days over a period of three months, an assessment of the change in pavement roughness with time was possible. Figure 31 displays the change in roughness for both the morning and afternoon conditions. The pavement changed in roughness 7% to 9% for the morning and afternoon readings, respectively. It is quite surprising that the morning readings had a perfectly linear relationship. The rate in change in roughness was 0.14 inches/mile/day and 0.10 inches/mile/day for the morning and afternoon conditions respectively. It should be noted that this increase in roughness occurred between 5 to 8 months after construction.

The reader is referred to Figure 17 which depicts an increase in roughness of approximately 21% between the 4th and 12th months after construction. That profile trace was obtained prior to 1960.

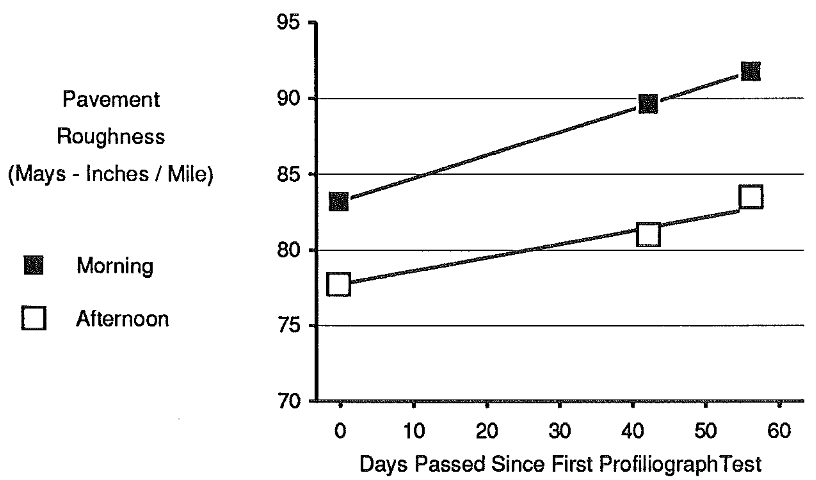


Figure 31 Change In Pavement Roughness Over Time

X DISCUSSION

Historically, the use of profilographs for construction quality control has consisted of evaluating concrete pavement profiles soon after placement. The paved surfaces have typically been assessed in accordance with a maximum acceptable profile index of 7 inches per mile. Recently, specifications have evolved from a simple acceptance criteria to an incentive / disincentive requirement. This appears to be an over extension of the capabilities of this measurement device.

The reproducibility of this device is not acceptable for the administration of incentive/ disincentive specifications currently being applied. Although, some controversy currently exists regarding the correlation between mechanical and automated devices which employ signal processing techniques, the actual problem is more basic than this recent development. The current specifications simply expect too much from the California profilograph. Francis Hveem vividly described the capability of this device in 1960[6]:

"While the profile index appears to be reasonably satisfactory for use in specifications, it fails to differentiate between bumps or irregularities of different shape and of different length and this numerical expression does not adequately emphasize the annoyance in terms of riding qualities generated by badly faulted pavements, for example. A somewhat more elaborate system of deriving a numerical index will be necessary if it becomes important to assign numbers to existing highways or airfields. It is to be doubted that there will be any adequate substitute for careful visual examination of the recorded profiles which convey information on the frequency, magnitude and shape of the inequalities, and it seems unlikely that all these factors can be adequately identified by any simple numerical expression even though the numbers are produced by feeding the profile record into one of the modern electronic calculators or data reduction "mechanical brains"."

Although Mr. Hveem could not begin to envision the power of modern day computers, he clearly assessed the limitations of the profile index and the need to evaluate the entire profile spectrum. With the current value of many of the incentive / disincentive specifications, it is important to assign numbers to existing highways and hence "... a somewhat more elaborate system of deriving a numerical index will be necessary...".

More recently, the study conducted by PTI reported "The use of profilographs to measure the roughness of new pavements where the acceptance criteria is below 7 inches/ mile is unacceptable unless the data acquisition is changed and the blanking band is eliminated from the data processing procedure."[1] The study further recommended the International Roughness Index (IRI) as a preferable numerical index.

A precision and bias statement for profilographs is necessary on a national level. The industry simply can no longer adjudicate measurement disputes in the field by retesting with other equipment and/or operators until a satisfactory measurement is achieved. There is a need to state quantitatively whether a machine and operator can perform in accordance with acceptable standards. The machine which provides the lowest profile index during retests is not necessarily the more accurate device. Measurement of pavement roughness is a stochastic process and as such measurement variability must be recognized, both high and low.

The dramatic effect that wheel eccentricity has on profile index, as reported by PTI, suggests that bicycle tires may not be well suited for use as a measuring wheel. Although they are convenient and inexpensive, the ability to maintain their roundness to almost perfect tolerances is questionable. At a minimum, standard methods for accurately checking wheel alignment must be developed and utilized. Annual calibrations and operator certifications also seem desirable. Non contact sensors would appear to have significant advantages over pneumatic tires.

Although a detailed statistical analysis was conducted for this study utilizing two levels of roughness, only one, one-tenth mile long section of pavement surface was used for all testing. This does not represent a spectrum of pavement surface types and roughness. It did however, allow the effect of the main variables and the interaction of the covariables to be clearly seen. Appendix A of this report includes graphs of the interactions between the main variables and the covariables. The strong interaction with some of the covariables suggests the difficulties in developing simple correlations between such factors as mechanical and automated devices by limited studies.

The industry "benchmark" standard of 7 inches/mile was established prior to utilization of slip form paving and long before electronic paver controls. Similarly, the relationship between this numerical index and ride quality was established on the suspension types and operating characteristics of vehicles from the 1950s and earlier. It is difficult to believe that modern day pavers produce similar quality pavements and that modern vehicles respond similarly to their 1950 counterparts. A clear need exists to re-examine the industry benchmark. The evaluation should consider the quality of pavement available from modern pavers and the response to ride quality provided by modern vehicles. Once the old standard has been verified or a new one established, incentive / disincentive specifications can then have meaningful value to agencies and contractors alike.

The industry "benchmark" may well be re-established as a function of the roadway classification or use. For example, an urban freeway with extremely high traffic volumes would seem to warrant higher standards of smoothness than perhaps rural roadways with significantly less traffic. One benchmark at any level does not appear appropriate for the wide range of pavement conditions found today.

Recent research has focused on establishing a relationship between Present Serviceability Index(PSI) and profile index. In this manner the initial construction roughness is tied to the expected pavement life through the serviceability index inherent in the AASHTO pavement design procedures. The current AASHTO design procedures suggest using an as constructed PSI of 4.5. The terminal PSI is often taken as 2.5 or 3.0. This change in PSI (i.e. 4.5 to 2.5) represents the "design" change in pavement serviceability over the life of the roadway. Since pavement designers are using an as constructed PSI of 4.5 it seems appropriate to expect this value from the construction industry. If it is not in fact obtainable, then it appears illogical to design to a standard which is not obtained in practice.

Research performed by Temple and Cumbaa related a Serviceability Index established with a Mays meter to the profile index determined with an Ames profilograph (see Figure 32)[18]. This research indicated that to achieve a Serviceability Index of 4.5 a profilograph index of 1 inch/mile would be necessary. A pavement constructed to the current 7 inch/mile "benchmark" would result in a Louisiana Serviceability Index of less than 4.0.

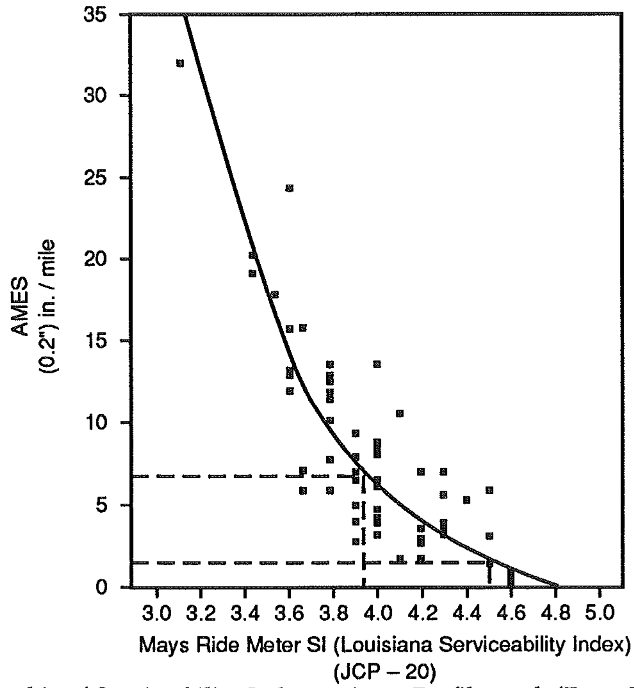


Figure 32 Relationship of Serviceability Index to Ames Profilograph (From Reference 18)

Research conducted by Walker and Lin also attempted to develop a correlation between Present Serviceability Index and profile index[19] (see Figure 33). This research established the Present Serviceability Index with a McCracken California profilograph. This study found that the 7 inch/mile "benchmark" resulted in a PSI of 4.1. It is also interesting to note that a profile index of 2 inches/mile only resulted in a PSI of slightly over 4.3.

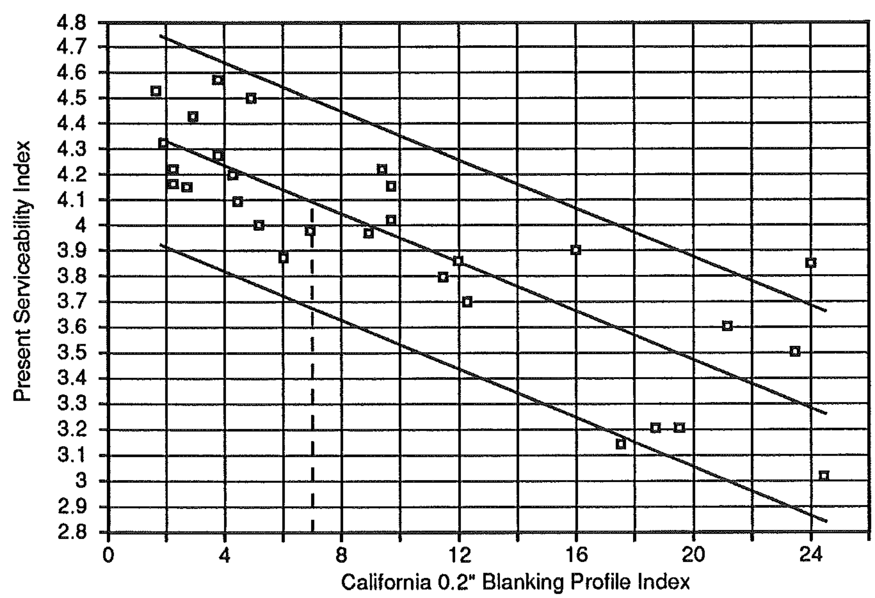


Figure 33 Relationship of Serviceability Index to California Profilograph (From Reference 19)

Both of these studies suggest that current design procedures are not in congruence with construction practice. If the AASHTO design procedures are to be accepted, then it appears appropriate to lower the roughness levels for new concrete pavements.

Significant spatial variability exists on pavement surfaces. This variability is not easily accounted for by averaging profile traces obtained in wheel paths. Currently, little or no information is available to determine if statistical sampling methods need to be developed to properly assess "true" roughness. Although the automated devices have significantly reduced test time, performing multiple runs under current procedures would seem impractical. A study should be undertaken to determine the required sampling frequency for proper determination of representative pavement roughness values. Recent research conducted by Janoff suggests that measurement of pavement roughness "... can be simplified to be based on profile type roughness measured in only one wheel path by a far simpler and less costly device than a profilometer."[20] This is contrary to the authors experience where a significant difference in roughness has been observed between wheel paths. Recent research conducted by SHRP suggests that variability between wheel path roughness levels does exist.[21]

The change in pavement roughness for both daily cycles and short term roughness increases is not well documented. Although the phenomenon has been reported for many years, its impact on profilograph testing has not been adequately recognized. This factor needs to be further defined so that its implications on test timing and methods can be properly evaluated. Additionally, if pavements constructed to "smooth" levels subsequently attain roughness levels equivalent to pavements constructed initially rougher after only a couple of years, the true value of an incentive specification is dubious at best. Research should be conducted to verify that pavements initially constructed smooth remain smoother throughout their life.

A surprising result from this study was the strong statistical interactions that were present between and among some of the variables and covariables. These interactions make it difficult to account for the variability present in profilograph testing with limited experimentation such as with one machine or one operator.

Manual trace reduction appears to have a larger effect on the resulting profile index than commonly believed. The average repeatability established in this study was approximately 0.94 and 1.88 inches/mile for the smooth and rough tracks, respectively. Although not rigorously evaluated, other studies found trace interpretation repeatability to be approximately 1 inch/ mile.[13,19] It is interesting to note that in one of these studies a computer generated profilograph trace was supplied to the operator for trace reduction. The null blanking band had been superimposed on the trace by the computer. Therefore, the null band (i.e. the template) was already depicted on the plot. The only variability measured was that of the operator's interpretation. This suggests that operator interpretation alone may approach a variability of 1 inch/mile. These results strongly encourage the use of the more efficient computerized profilographs.

As incentive specifications reward contractors for producing ever smoother pavements, consideration should be given to the effects this may have on concrete mix design and resulting concrete quality. Mix designs which promote smooth pavements may produce surfaces with greater attrition and hence lower skid properties with time. Smooth pavement surfaces should be provided in concert with durable concrete pavements and not in lieu of them.

Phase two of this research is designed to develop a precision and bias statement for profilograph testing. It is anticipated that the roadway profile, established with a KJ LAW 690DNC profilometer, will be used with a computer program which simulates a profilograph to establish the "true" profilograph readings.

XI RECOMMENDATIONS

The 7 inch/mile industry standard or "benchmark" should be re-evaluated. A field survey should be conducted on modern era pavements to establish an appropriate roughness level for construction acceptance. This study should, at minimum, consider the roadway function such as high Vehicle Miles Traveled (VMT) urban or low VMT rural roadways. The study should also include a panel evaluation which relates current vehicle response and human perceptions of roughness to current construction standards. There is no doubt that the industry "benchmark" should be on the order of 5 inches or less for high VMT urban freeways.

The California profilograph does not appear to have the accuracy necessary to appropriately administer a viable incentive/disincentive specification in view of the smoother and smoother pavements now possible. The industry should move away from the profile index standard and adopt some other summary statistic such as the International Roughness Index (IRI), RMSVA, etc. Utilization of these or other acceptable profile-based statistics would require more accurate measurement equipment. They would also provide a cradle to grave roughness statistic. That is, the statistic which would be used by the pavement designer could be directly related to the as-constructed roughness and future pavement performance.

Improvements in concrete pavement ride quality appear to have been brought about largely by the adoption of incentive/disincentive specifications and improved construction equipment. These improvements should continue to be encouraged by such specifications. However, the devices used for acceptance testing must be commensurate in accuracy with the monetary actions represented by these specifications. If this is not possible, then specifications which only place a maximum allowable roughness level should be utilized.

If profilographs are to continue to be used for PCCP acceptance, annual operator certification and equipment calibration should be conducted to ensure proper test procedures and equipment operation. All testing should be performed with the automated devices. Guides should be used to position profilographs in the proper wheel paths.

The Arizona Department of Transportation (ADOT) should develop a plan to move away from the profilograph for the acceptance of concrete pavements. A new system using more accurate equipment and analysis methods should be developed to administer incentive/disincentive specifications. The plan should include a study which determines the acceptable number of tests to adequately describe the "representative" roughness level. The long term plan should require construction acceptance to be performed with a profilometer.

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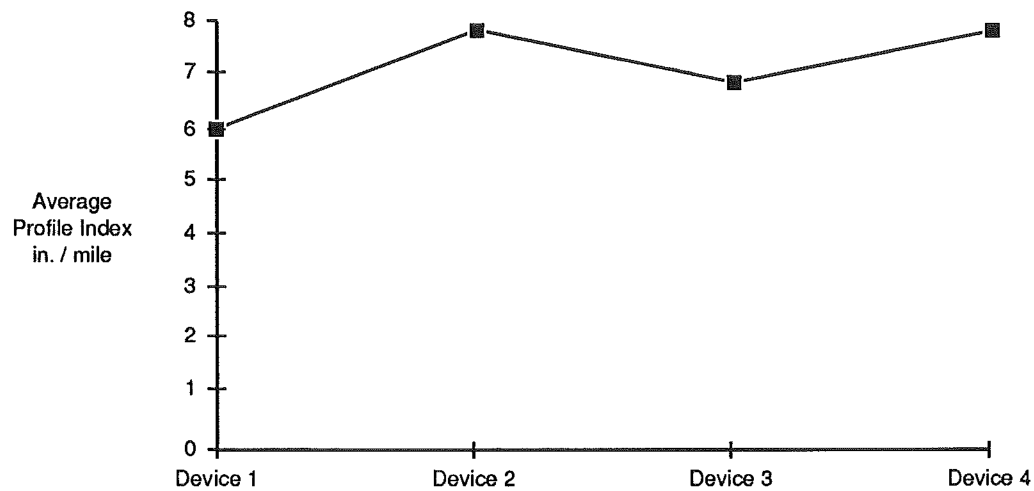
Appendix A – Summary Of Test Results For Main Study And Interaction Plots

SUMMARY OF TEST RESULTS FOR THE MAIN STUDY

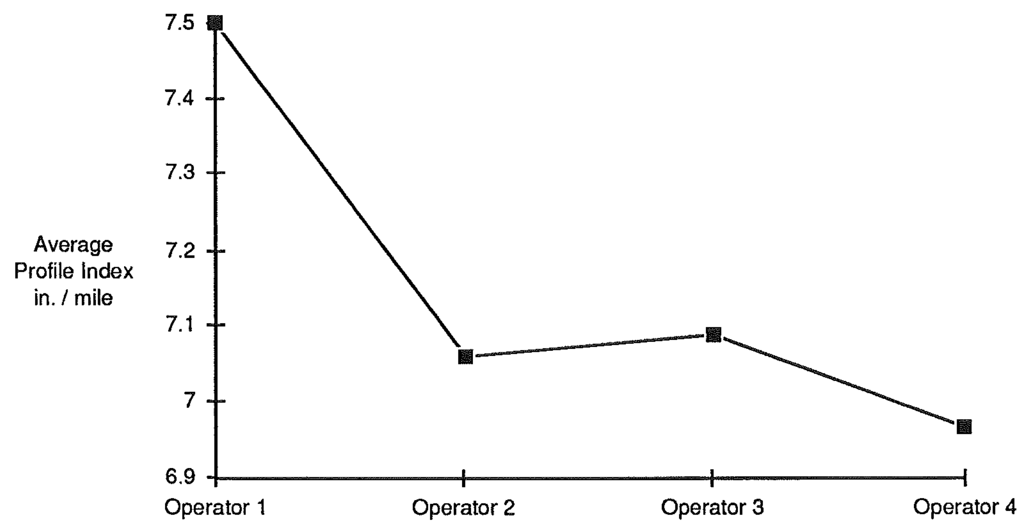
RUN NUMBER	OPERATOR NUMBER	DEVICE NUMBER	PROFILE INDEX (IN/MILE)		LANE AVERAGE
			TRACK #5	TRACK #6	
1	1	M1	4.0	10.0	7.00
2	2	M2	5.0	10.0	7.50
3	3	E3	6.0	8.0	7.00
4	4	E4	6.0	10.0	8.00
5	2	E3	5.0	7.5	6.25
6	1	E4	6.0	11.0	8.50
7	4	M1	4.0	7.0	5.50
8	3	M2	5.5	9.0	7.25
9	3	E4	7.0	8.0	7.50
10	4	E3	5.5	7.5	6.50
11	1	M2	5.0	11.0	8.00
12	2	M1	3.5	8.5	6.00
13	4	M2	5.5	10.5	8.00
14	3	M1	5.0	7.0	6.00
15	2	E4	7.0	9.0	8.00
16	1	E3	5.0	8.5	6.75
17	4	E3	5.5	8.0	6.75
18	2	M1	3.5	7.5	5.50
19	3	E4	6.5	10.0	8.25
20	1	M2	5.0	11.0	8.00
21	3	M1	4.0	7.0	5.50
22	1	E3	6.0	8.0	7.00
23	4	M2	5.0	11.0	8.00
24	2	E4	6.0	8.5	7.25
25	2	M2	6.0	11.0	8.50
26	4	E4	5.5	8.5	7.00
27	1	M1	3.5	8.5	6.00
28	3	E3	6.5	8.5	7.50
29	1	E4	6.5	11.0	8.75
30	3	M2	6.0	9.5	7.75
31	2	E3	6.5	8.5	7.50
32	4	M1	4.0	8.0	6.00

Note: A run consisted of a chain of two trips in one lane. One trip was made on a rough wheel path (track #6) and a return trip on a smooth wheel path (track #5)

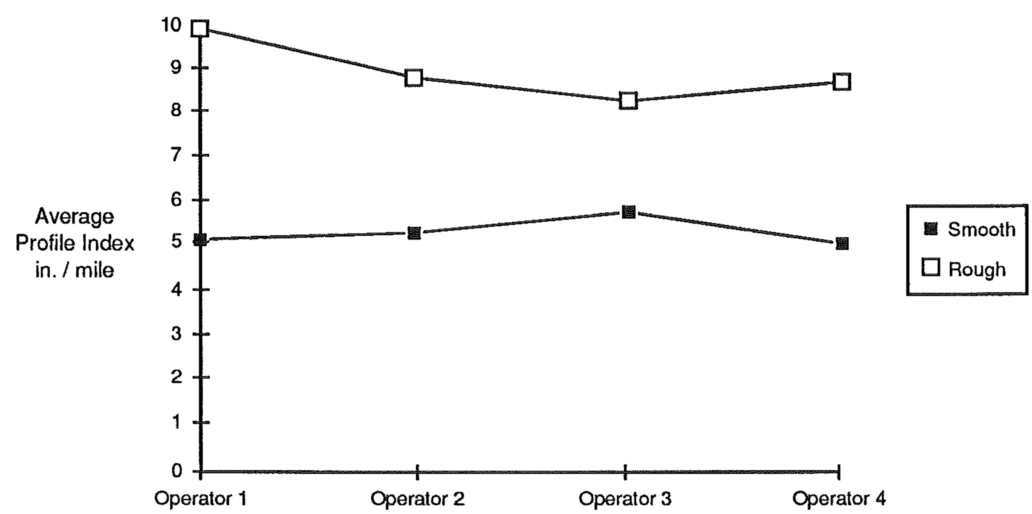
Appendix A – Summary Of Test Results For Main Study And Interaction Plots



Profile Index vs Devices

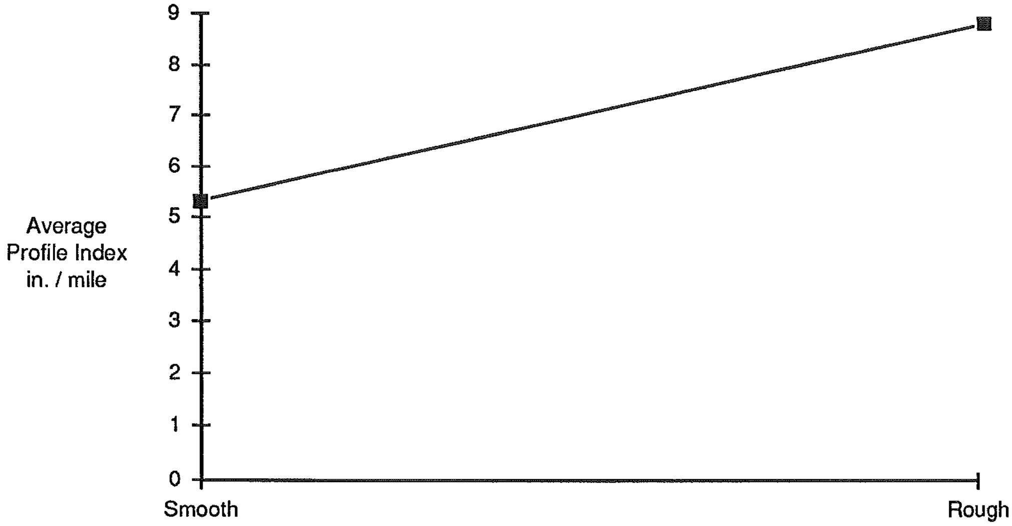


Profile Index vs Operators

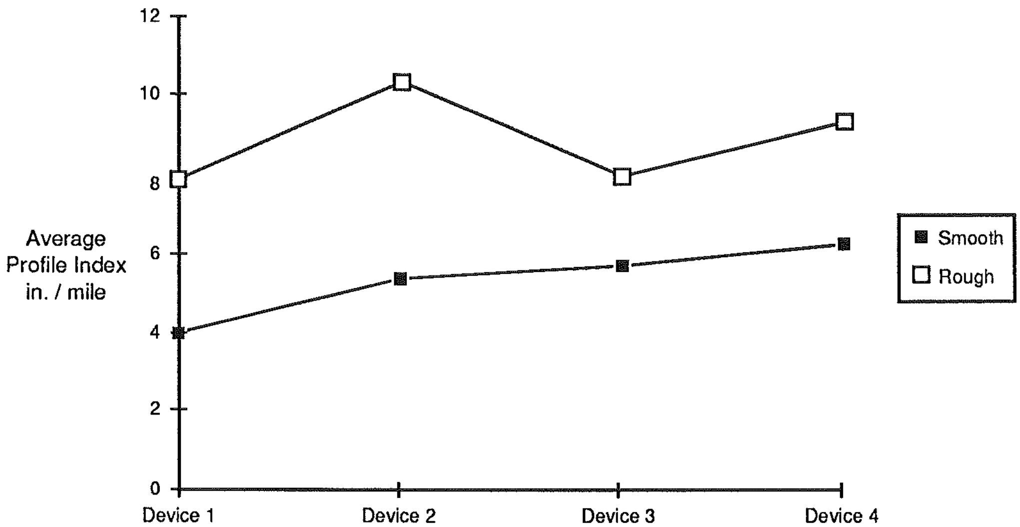


Profile Index vs Operators for Smooth and Rough Roads

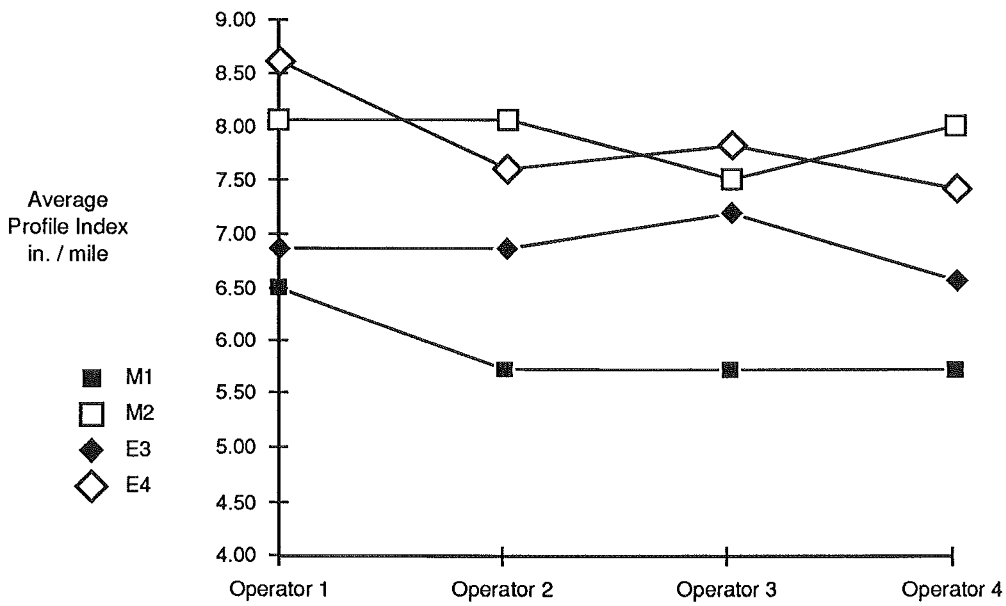
Appendix A – Summary Of Test Results For Main Study And Interaction Plots



Profile Index vs Road Smoothness

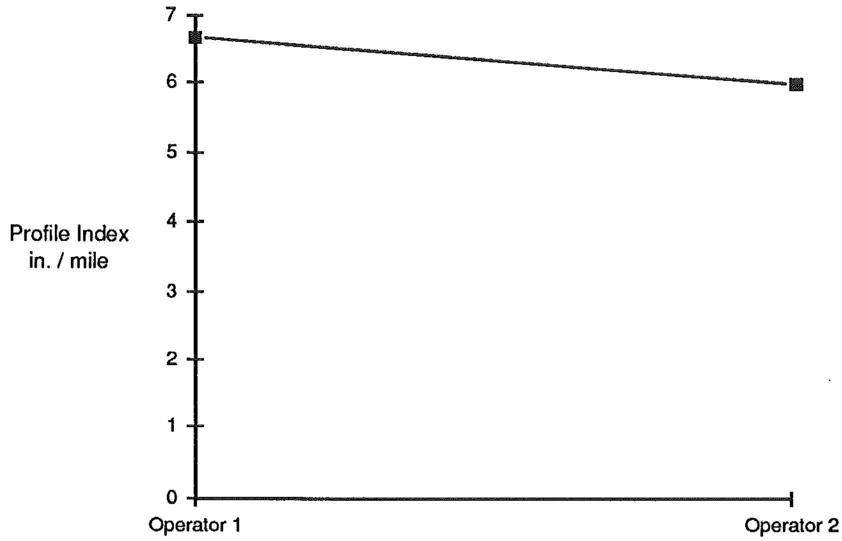


Profile Index vs Device for Smooth and Rough Roads

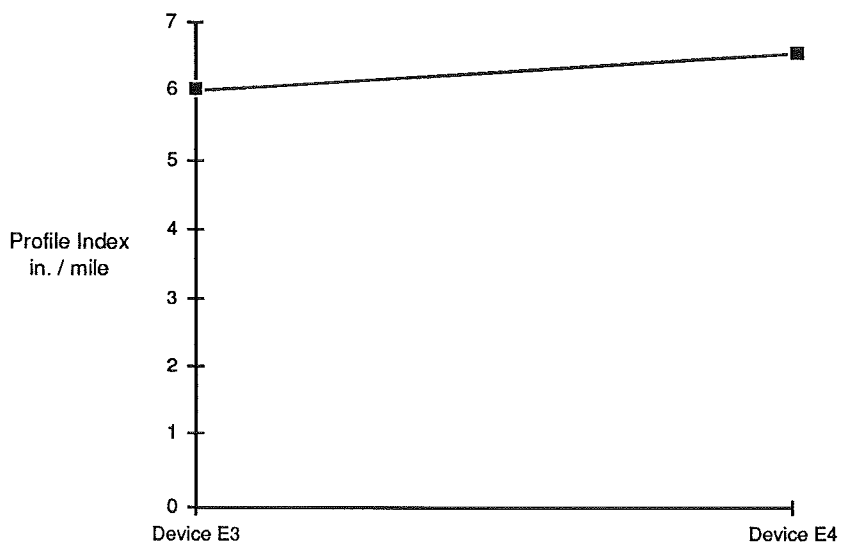


Profile Index vs Operators for Each Device

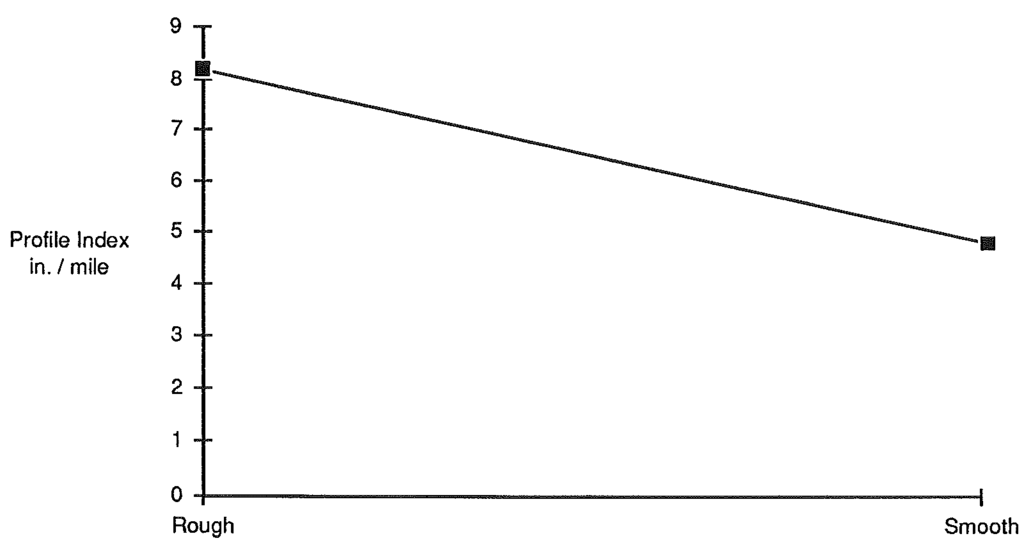
Appendix A – Summary Of Test Results For Main Study And Interaction Plots



Profile Index vs Operators for Automated Devices

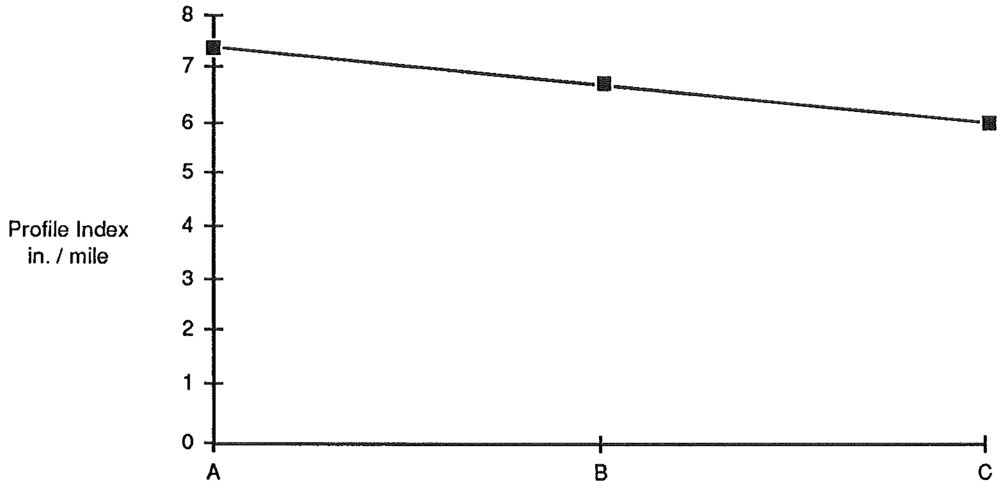


Profile Index vs Devices for Automated Devices



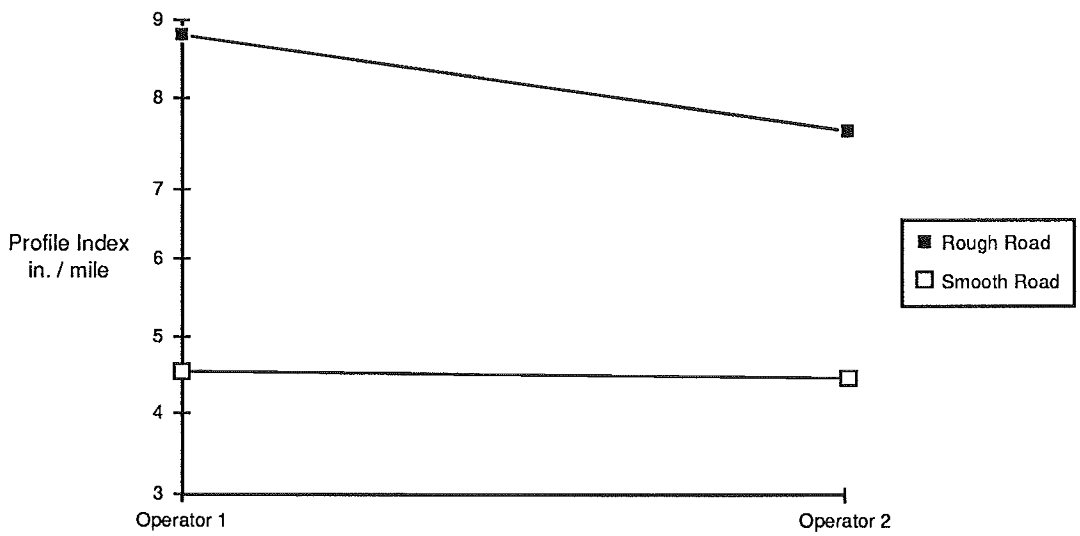
Profile Index vs Pavement Smoothness

Appendix A – Summary Of Test Results For Main Study And Interaction Plots

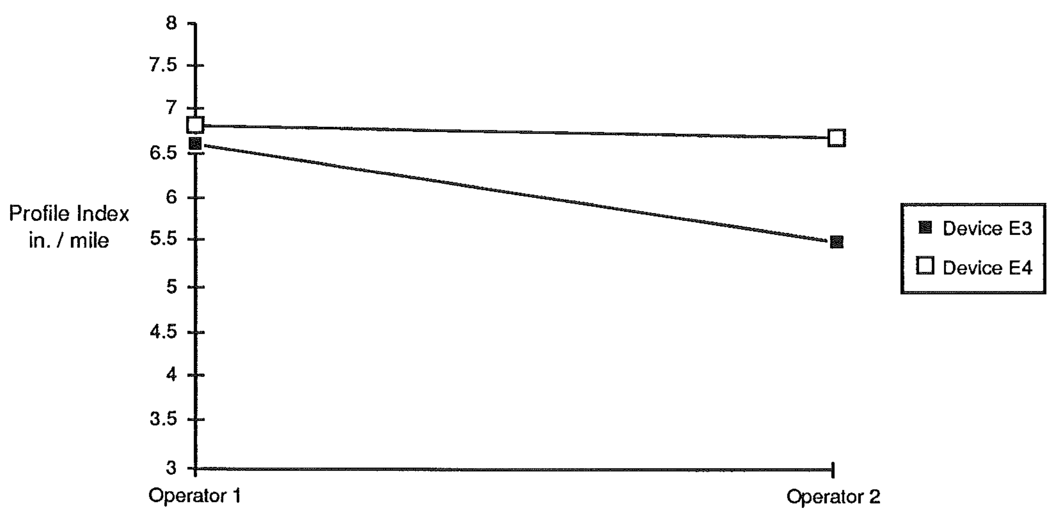


Filter Settings: A = 8000, B = 6000, and C = 4000

Profile Index vs Filter Settings for Automated Devices



Profile Index vs Operators for Rough and Smooth Pavements



Profile Index vs Operators for Devices E3 and E4

Appendix B – Summary Of Test Results From Automated Devices At Different Filter Settings

RUN NUMNER	OPERATOR NUMBER	DEVICE NUMBER	FILTER SETTING	PROFILE INDEX (IN/MILE)		LANE AVERAGE IN/MI
				TRACK #5	TRACK #6	
1	2	E4	B	4.5	8.0	6.25
2	1	E3	A	5.0	9.5	7.25
3	2	E3	C	3.5	6.0	4.75
4	1	E4	B	4.0	9.5	6.75
5	1	E4	C	3.0	8.5	5.75
6	2	E3	A	4.0	8.0	6.00
7	1	E3	B	4.5	8.0	6.25
8	2	E4	C	4.5	7.0	5.75
9	1	E4	A	6.0	9.5	7.75
10	2	E3	B	4.0	8.5	6.25
11	2	E4	A	6.5	9.5	8.00
12	1	E3	C	4.5	7.0	5.75
13	2	E3	A	4.5	8.0	6.25
14	1	E4	C	3.0	6.0	4.50
15	2	E4	C	5.0	7.0	6.00
16	1	E3	B	3.5	8.5	6.00
17	2	E3	B	3.5	7.5	5.50
18	1	E4	A	6.0	11.5	8.75
19	1	E3	C	4.0	8.0	6.00
20	2	E4	A	5.5	8.0	6.75
21	1	E3	A	5.5	11.0	8.25
22	2	E4	B	5.0	9.0	7.00
23	1	E4	B	6.0	8.0	7.00
24	2	E3	C	3.0	5.5	4.25

Notes: a. A run consisted of a chain of two trips in one lane. One trip was made on a rough wheel path (track #6) and a return trip on a smooth wheel path (track #5)
b. The filter setting levels were : (i) A = 8000; (ii) B = 6000; and (iii) C = 4000 .

Appendix C – Summary Of Profilograph Trace Readings (in/mile) From Four Operators

		SMOOTH WHEEL PATH (5)				ROUGH WHEEL PATH (6)			
	FIRST/SECOND	DEVICE M1		DEVICE M2		DEVICE M1		DEVICE M2	
OPERATOR NO.	READING	RUN #1	RUN #10	RUN #2	RUN #12	RUN #7	RUN #13	RUN #8	RUN #15
1	1	5.0	9.0	5.5	8.0	8.5	9.0	11.5	12.0
	2	3.0	5.0	3.0	6.0	7.5	8.0	10.0	11.0
2	1	3.5	4.5	5.0	6.5	7.0	8.0	9.5	10.5
	2	3.0	3.5	6.0	7.0	7.0	7.5	16.0	11.5
3	1	1.5	3.0	1.5	2.5	7.0	6.5	8.0	9.0
	2	2.0	2.5	2.5	3.0	7.5	7.0	9.0	6.0
4	1	1.5	2.5	3.0	3.0	6.5	7.5	9.5	9.5
	2	1.5	3.0	2.0	2.5	7.0	5.5	6.5	8.0

Appendix D – Make And Purchase Dates For ADOT Profilograph Machines

PROFILOGRAPH IDENTIFICATION		MAKE	PURCHASE	REMARKS
STUDY ID NO.	ADOT NUMBER		DATE	
M1	32919	COX & SONS	4/26/67	Converted from mechanical to electronic 3/20/91
M2	77400	HVEEM	12/11/84	Mechanical device
E3	84801	HVEEM	4/1/86	Converted from mechanical to electronic 3/22/90
E4	96943	COX & SONS	3/6/89	New electronic device