MEASURING THE SMOOTHNESS OF NEWLY CONSTRUCTED CONCRETE PAVEMENT FOR ACCEPTANCE SPECIFICATIONS

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A smooth highway surface is recognized as an important characteristic for achieving good service life and user comfort. A 10-foot straight edge was the traditional instrument used by contractors and owners to check surface deviations until the Profilograph was developed in California in the 1960s, and utilized as a means of evaluating pavement smoothness. In the last decade many highway engineers have noted a decline in initial pavement smoothness and, as a result, other state agencies have incorporated versions of the Profilograph into their acceptance standards. This led AASHTO in 1984 to conduct a survey into smoothness specifications and to recommend a draft guide specification. The Texas State Department of Highways and Public Transportation (SDHPT) engaged the Center for Transportation Research (CTR) at The University of Texas to evaluate this specification with a variety of roughness devices.

The paper presents a brief historical background and reports the key results of an AASHTO survey to ascertain state's practices. A modification to the AASHTO guide specification is then discussed, and implications of the bonus and penalty categories discussed. A high resolution profiling device, the Dipstick, which can be used to quantify pavement surface data, has been tested with other roughness devices and the results are presented. Finally, a California-type Profilograph was employed on newly constructed reinforced concrete to test the proposed specification prior to its trial adoption. Problems with the Profilograph were identified which could make the proposed standards difficult to implement. CTR staff believe that a combination of Profilograph and Dipstick instruments, together with a modification to the categories within the Texas draft specification, would result in a more equitable and enforceable standard.

Key Words: Smoothness standards, Profilograph, AASHTO reliability survey, Dipstick, roughness measuring devices, Texas smoothness specification, incentive payments.

INTRODUCTION

Effectiveness and efficiency are two central objectives in the evaluation of transportation investment programs. In providing concrete highways, these objectives can be specifically defined as user acceptance and adequate service life in years. Users, whose importance as taxpayers should not be forgotten, expect a good riding surface in terms of both subjective comfort and objective vehicular wear and tear. Highway agencies seek to maximize the impact of budgetary levels and it is now broadly accepted that economic efficiency is best achieved through some measure of life cycle costing. Highways that are constructed to high standards of smoothness and structural strength, while meeting acceptable drainage and skid resistance specifications, are associated with good riding characteristics and long life. The objective of this paper is to report the progress staff at The University of Texas at Austin Center for Transportation Research (CTR) have made in developing standards, instrumentation and routines that can be used by the Texas State Department of Highways and Public Transportation (SDHPT) to develop smoothness acceptance specifications on newly constructed concrete pavements.

Smoothness and roughness are different values of a scalar function describing a variety of absolute surface profiles and wavelengths (1). A profile has a complex structure which can be decomposed into different wave-lengths and amplitudes, varying somewhat with the type of surface. It is the interaction of these profile elements with vehicle responses dependent upon the suspension and tires which gives rise to user perceptions of discomfort and vehicular damage. As a consequence such interactions have received much attention in the development of roughness measurements. Currently, roughness is defined by ASTM as "the deviations of a surface from a true planar surface having characteristic dimensions that affect vehicle dynamics, ride quality, dynamic loads and drainage" (2). The first two are associated with user acceptance and the remainder with service life. A user is adversely influenced by any undesirable combination of surface profile, vehicle design characteristics and travel speed. Construction smoothness specifications concentrate on the profile issues where roughness can be divided into three components; transverse, longitudinal and vertical variations which impart roll, vertical acceleration, and yaw, in varying degrees, given the combination of vehicle characteristics and speed. Previous studies have established that longitudinal roughness is the major contributor to undesirable vehicle behavior (3), and it is this phenomenon which is the focus of acceptance specifications.

BACKGROUND

Equipment for the measurement of roughness has been available for almost 60 years (4) and there was increasing interest in the late 1950s as a result of both the AASHO road test and the formation of the Interstate highway program. AASHO road test research staff Carey and Irick provided engineers and planners with a tool for evaluating pavement performance when they developed the "serviceability—performance" concept (5). The AASHO profilometer, a multi-wheeled manually operated device generating slope variance as a roughness measure, was used to profile highway test sections subsequently rated by panels of highway users. The result was the present serviceability rating or index—PSI—which is still used today. Since establishing PSI panel values is both expensive and inconvenient, considerable effort was expended in relating PSI scores to the output of mechanical devices that could be used to monitor pavement performance over highway networks.

The research emphasis of recording pavement serviceability for monitoring and managing networks revealed a need to develop devices generating numerical values for application at the project level. The Interstate program called for the rapid development of a national network of durable, high quality pavements and attracted the attention of engineers responsible for maintaining quality control standards. In general, a 10-foot straight edge was used to check pavement surfaces, but serious consideration was also given to the possibility of using a more effective instrument and more precise measurement standards during the Interstate construction period.

California became one of the first states to apply longitudinal roughness controls to construction quality controls when one of its engineers, Francis Hveem, invented and applied a manually operated, multi-wheeled travelling vertical offset measuring device which became known as the California Profilograph. This device records the pavement surface profile on a paper roll from which a Profile Index (PI), in units of inches per mile, can be interpreted. Previously, a straight edge—usually 10 feet—was employed to check surface roughness behind the paver and corrections were required where deviations exceeded some specified depth, such as one-eighth inch. California changed its acceptance specifications to include its Profilograph in the 1960s, but few other states followed this example until the 1970s. This was due in part to the feeling that existing specifications were adequate and in part to the fact that the Profilograph exhibited certain problems and no other alternative instruments were available which were convenient to use.

Other monitoring and calibration profile devices were either mounted inside vehicles or pulled by vehicles, and this made them too heavy to operate on newly placed concrete pavements during the initial curing stages. Also, the dynamic operation of the devices sometimes made it difficult to accurately locate pavement surface defects, where corrective action was required. Subsequently, highway officials noted increasing problems in pavement quality control and moved to change their construction acceptance specifications. Invariably the California Profilograph was adopted as the control device. This change occurred in spite of difficulties with the Profilograph's repeatability, (for example, Ref 6), which was partly due to an inability to isolate the effect of long wavelengths in the pavement profile.

AASHTO SURVEY

By the mid 1980s, there was a consensus of opinion among highway engineers supporting the idea of adopting standardized pavement smoothness specifications. As a consequence, AASHTO conducted a survey in 1984 to identify those states using smoothness controls, document their experience, and develop a unified set of recommendations. The results, for 39 states (7), provide some interesting insights into the status of pavement quality specifications. The survey data indicates that the typical average respondent used both a ride and a bump specification. Ride quality was controlled using a California Profilograph with a PI acceptance range of up to 12 inches per mile. Bump deviations were controlled by using a 10 foot straight edge. Control equipment was provided by both contractor and state, the latter to cross check the device provided by the contractor. State officials were responsible for data interpretation, since this is a highly sensitive issue. Finally, while on average there were no monetary incentives for work exceeding acceptance levels, a monetary penalty was linked to poor quality work. A telephone survey, conducted by CTR research staff, of engineers in nine states using smoothness specifications confirmed the efficacy of the California Profilograph. In spite of the question regarding the profile resolution, the device had an extremely beneficial effect on quality controls, and its adoption had resulted in higher standards of riding surface smoothness.

DRAFT TEXAS SPECIFICATIONS

AASHTO produced a set of guide specifications and CTR staff were directed to develop a draft specification suitable for the Texas SDHPT. After a number of internal meetings, the Texas SDHPT specification committee recommended testing a specification comprising the following key elements (8).

1. The procedure should apply to contracts where design speed exceeded 40 miles per hour on the travel lane, thus eliminating city streets, frontage roads, and freeway ramps. This was both to control the CTR evaluation more closely and to restrict the focus of smoothness controls to those sections of highway where roughness was likely to strongly influence perceptions of user serviceability. Frontage road smoothness, for example, was not considered critical to user ride quality since it was affected by combinations of slower speeds, intersections, and property access driveways.
2. The control instrument should give a measure of longitudinal roughness in Profile Index units of inches per mile. The final index should be an average of both wheel paths on each travel lane of the contract.
3. It was decided to incorporate a bonus for high quality work, an acceptance band for full contract price and some system of penalties for poor work. The bonus scheme was to apply to one-tenth-mile (528-foot) sections of the contract. This element is discussed in more detail in following sections.
4. The recommended instrument was a California-type Profilograph though other instruments capable of providing acceptable profile data were not excluded from the evaluation tests. Equipment would be provided by the contractor but there would be a Texas SDHPT capability to compare and check the performance of the instrumentation with similar state equipment. A calibration system and operator's guide were required and, in the case of the California-type Profilograph, would be based on existing documentation.
5. The 10-foot straight edge was retained for smoothness control on ramps and access and transfer points, together with bump control along the main travel lanes. Other equipment that could perform these functions would be evaluated.
6. The basic procedure would be tested by CTR both in small focussed work in key areas and in its entirety on a major engineering contract in late fall 1988.

This paper reports on a variety of aspects of this work with reference to smoothness criteria, instrumentation for measuring profiles on newly laid concrete pavements and incentives.

SMOOTHNESS CRITERIA

Details of the draft criteria based on Profile Index values are given in Table 1 and drawn in Fig 1. Table 1 gives ranges of PI values in inches per mile, indicates whether this range is acceptable or needs rectification to meet the Texas SDHPT standards, and finally, provides a financial adjustment factor for each range. For example, the 0 to 3-inch range is acceptable with no rectification and a bonus of 5 percent of unit price is paid. If the profile lies within the 7 to 10-inch range, the contractor is paid full unit price since the work meets acceptable specification, again with no rectification required but also no bonus payment. Profiles in the range of greater than 10 and less than 15 inches per mile give the contractor a choice. The work can either be handed over to the Texas SDHPT at a penalty—see final column of Table 1 for details—or it can be brought back into the 7 to 10-inch acceptance range (for example, by grinding) where the full contract unit price is paid. These interesting choices reduce to financial trade-offs for the contractor which will have to be examined in future CTR work. Finally, section profiles with a PI greater than 15 inches per mile will require mandatory rectification to under 10 inches, when full unit price will be paid.

A schematic of the draft specification is shown in Fig 1 and highlights the essential components of acceptance and rejection boundaries incorporated into optional bonus and improvement schemes. CTR tests of the ranges of these categories, particularly the transition points, are likely to lead to their review and modification. Currently, the ranges are tentative and lack corroborative data that support the precise cut-off values between categories, in general, and within the conditional acceptance range of PI values, in particular. The financial elements of a quality control specification must be carefully adjusted to induce the desired response from the contractor and the characteristics of such inducements are now discussed.

INCENTIVE AND PENALTY SCHEMES

The provision of penalty or bonus systems, either separately or in combination, has been proposed for a number of highway acceptance standards, for example, pavement thickness. Proponents of incentive schemes believe that the contractor will ensure that his product meets or exceeds control standards providing he is induced to do so by a sufficient financial reward. Furthermore, when contracts are being let, well managed contractors will take some or all of the bonus into account when developing their bids—in effect discounting the bonus elements into the base price. This may have the desirable effect of restricting the success of cut-price contractors on highway work and result in a wider set of benefits than simply ensuring surface profile quality.

Incentive schemes should be guided by three "E's"—equity, enforcement, and efficacy—so that standards are seen to be fair, enforceable by highway engineers, and capable of providing the desired effect. It has been suggested (9) that incentive schedules should retain payments at the time of construction to cover the extra future cost forecast as a result of deficient quality work. CTR staff believe that such a feature would not meet the equity criterion since forecasting the timing and extent of the deficiency would be extremely difficult and contentious, particularly in respect to determining withholding values. It was therefore decided to concentrate on practices that would deal with deficiency issues as they arose within the contract period, and not defer them to some future date.

The financial elements of bonus, acceptance, and penalty clauses need to be structured so that they are as simple as possible, on the basis that complexity will obscure effectiveness. Regarding the draft specification in Table 1, it is likely that the conditional section is too segmented. This is always a problem when a stepped, as opposed to a continuous, incentive scheme is adopted. Stepped schemes also raise the issue of fairness in respect of the breaks between steps and the ability of the chosen measuring device to accurately position a profile within the stepped categories. If we take the bonus section, for example, is it equitable that a PI in the 5 to 7 inch range gets a 1 percent bonus while a PI in the 0 to 3 range gets 5 percent? Is it five times better or is the bonus allocated in an arbitrary rather than scientific manner?

A major problem associated with pay rewards is the basis for computing the values, particularly as they relate to the financial consequences of both good and poor quality work. This can be illuminated by considering the example of rewards for meeting consolidation standards in concrete pavement construction work (10). The effect of consolidation on compressive strength can be determined through estimating flexural strength and then inputting this value into the AASHTO design guide equation (11) which predicts equivalent single axle loads as a function of several parameters including this variable. The effect of consolidation on pavement service life can be dramatic. In the FHWA report 87/095 (10) it is shown that for straight line traffic growth and for a 600 psi (4.1 MPa) flexural strength at 100 percent consolidation, predicted service life falls from a designed 20 year life, through 10.4 years at 95 percent consolidation, to 5.4 years at 90 percent consolidation. The financial ramifications of these data cannot be directly reflected in penalty clauses, since the costs associated with such truncated service lives overwhelm construction costs, particularly if user costs are contemplated in addition to agency costs. On even a lightly trafficked highway, the prolongation of service life by only a few years dwarfs the bonus payments contemplated by even the most generous incentive schemes.

Therefore, the calculation of direct benefits or costs is not the appropriate bench mark for bonus or penalty payments and some other means of determining levels has to be developed. It may be appropriate to identify those specific issues within each acceptance category, namely an inducement level to get high quality work, a nominal acceptance range that reflects adequate ride quality and service life, an adjusted payment schedule for acceptance at a slightly deficient standard, and finally a level where ride quality would be unacceptable and service life reduced. CTR research will first establish the acceptable range and then determine the level beyond which ride quality becomes unacceptably high. Bonus limits will then be established and a continuous function fitted through the stepped categories shown in Fig 1. Such functions could take various forms. One method would be to fit two non-linear relationships through the bonus and conditional acceptance stages, while retaining the linear acceptance category. However, this arrangement is rather cumbersome to implement and somewhat illogical. If it is desirable to obtain higher levels of smoothness, then it is more equitable to have a continuous function throughout the entire range of acceptable values. An example of this is given in Fig 2, where the contractor receives financial incentives for all increases in smoothness. Further statistical modifications to this could be devised to incorporate the variability of the Profilograph and these will be evaluated at a later stage of the research.

INSTRUMENTATION

The draft specifications identified a California-type Profilograph as the recommended instrument although CTR staff were given the option of identifying and testing a variety of profile devices. Table 2 classifies such instruments from the World Bank (12) and other sources (13,14,15), based on a series of tests and analyses conducted in Brazil and the United States. Class 1 and 2 techniques and equipment can move between categories depending on the horizontal distance between readings (measurement interval) and the accuracy of the output data. Rod and level data, for example, if taken at intervals greater than 2 feet would produce a Class 2 profile rather than the Class 1 specified in Table 2. The Profilograph is rated as a class 3B, which indicates that it is not considered a high resolution device. Nevertheless, due to its impressive performance in getting contractors to improve surface quality, its low cost, the familiarity of the construction industry with the device, and its ability to rapidly operate on a newly laid surface without causing damage, the Texas SDHPT was keen on retaining it as the main control device. CTR tests have employed a McCracken manufactured California Profilograph, which has certain operating advantages over other types. Details are given in Fig 3 and further information can be found in readily available reports (16,17). The machine is manually propelled at a slow walking pace, around 3 miles per hour, and the vertical displacement of the centrally mounted bicycle wheel is recorded onto a roll of paper in the form of a profile. The paper output for a wheelpath is then interpreted by positioning a blanking band (0.1-inch spaces for the CTR's research) through the profile and measuring deviations from a benchmark center line of 0.2 inch. These are then summed to give the PI numeric.

The length of the device (about 33 feet) limits the degree of curvature that it can tolerate on test sections, a constraint which worsens with any increases in superelevation. The design and size of the machine require it to be dismantled and trailored to each test section although this may not be critical on a single highway contract. The Profilograph requires calibration, though the procedures are limited to testing the distance and vertical displacement mechanisms on the device. Since the California Profilograph is not considered a high resolution profile device, research staff were keen to investigate other devices capable of giving absolute profiling data of a higher quality in order to supplement the California-type Profilograph PI output. The instrument currently best suited to these needs appeared to be the Dipstick and one was obtained for evaluation purposes.

The Dipstick, manufactured and patented by the E.W. Face Company, is a portable elevation measuring device originally designed to evaluate the quality (flatness and levelness) of concrete floors. The Dipstick, shown in Fig 4, comprises a boxed pendulum which detects differences in elevation between two legs fixed one foot apart. The operator rotates the device from one leg to the other across the desired profile and after each move the pendulum, when in a balanced state, sends the new change in elevation to an 18K on-board computer for storage and programming needs. For the purposes of measuring longitudinal profiles, a chalk line is made down the selected wheelpaths on the pavement and the operator walks the device down the line. The device emits a noise when the pendulum has become unbalanced which gives the operator time to steady the instrument in preparation for the next elevation reading. Data from the small computer are then down loaded to an IBM compatible PC which then permits data to be displayed, manipulated, and reported through a variety of programs. More details are available in references 16 and 18, and the next section deals with a series of tests comparing the performance of the Dipstick with other high quality profiling devices.

DIPSTICK EVALUATION

These tests were performed on four different roadways around the Austin, Texas area during the spring months of 1988. The chosen sections were first surveyed using a local contractor's rod and level crew to give a Class I instrument's absolute profile as a benchmark to judge the performance of the Dipstick. The Texas SDHPT modified K.J. Law SD 690 Profilometer was also used to measure two of the test roadways and the results were compared to the rod and level as well as the Dipstick data (18). A brief summary of the results of this evaluation procedure is now presented.

The evaluators were interested in determining whether the profile data output from the Dipstick instrument was repeatable and accurate. The Dipstick's basic output is a series of elevation changes calculated from the previous elevation while rod and level surveys are a series of independent elevations. It was therefore important to address the issue of operator error and bias and deduce whether this prejudiced the potential usefulness of the Dipstick as a smoothness control device. The experiment was also intended to identify as many mechanical and/or software problems associated with the operation of the Dipstick as could be observed within the limited time allotted. The test sites for this evaluation included both concrete and asphalt pavements as well as smooth versus rough pavements of each type so that the Dipstick's response could be evaluated over a spectrum of surface types and conditions.

A 970-foot section of smooth asphalt pavement was measured twice with the Dipstick. The first run was made utilizing several different operators while the second run was made with a single operator. The resulting elevations were plotted and overlayed on a single graph to check the repeatability of the instrument. The slight difference in the Dipstick's elevation readings from the two runs compared with the relatively large total change in the roadway elevation made the two graphs appear as a single line. The difference between the end of the first run and the end of the second run was calculated to be 1.25 inches. Another set of measurements was used in the repeatability determination. A 100-foot section of concrete pavement was measured and the readings were both manually and automatically recorded. The direction of the readings was reversed, and the resulting profile plot can be viewed in Fig 5. The difference in elevation at the end point was calculated to be 0.185 inch.

The operator error determination was accomplished by a closure method. The process entails a single operator walking the Dipstick down a wheelpath, over a known distance, back up and parallel to the original wheelpath, and finally, over to the original starting point. Figure 6 graphically presents the results of this exercise, based on a CRCP section located at Balcones Research Center (BRC), Austin, Texas. The operator error associated with the Dipstick can be calculated by finding the difference in elevation from the first and last reading (0.003 inch in this case) and dividing by the number of readings taken. The operator error for this section was calculated to be 0.002%. Another section of pavement was used for this determination and the difference between the first and the last elevation readings was found to be 0.019 inch over 415 readings, yielding an operator error of 0.0045%, which can be regarded as virtually negligible.

The Dipstick measures to the nearest 0.001 inch and the feet are leveled to within 0.003 inch of each other while the best rod and level survey can read to 0.01 foot and estimated to the nearest 0.001 foot. These results confirm that the instrument is both accurate and repeatable with a very small associated operator error. In addition, the measurements are recorded at a much faster rate than with the rod and level, which makes it very cost-effective. Problems were encountered during the tests but were generally of a minor nature. It was noted that, on one section with a 2 percent grade, the metal feet slipped which resulted in an accumulated error at the end of the test section when the data were plotted. The manufacturers have now added a non-slip material to the feet to address this problem and have also changed the software to improve performance.

The Texas SDHPT modified KJ Law SD 690 Profilometer was run three times over a 970-foot section of asphaltic roadway surveyed by the Dipstick and Class 1 rod and level techniques. The elevations of the three runs in the left-hand wheelpath were averaged and plotted. The roadway slope as calculated from the rod and level survey and was added to the Profilometer's x-axis (distance). The rod and level survey, the Dipstick, and the Profilometer elevations were plotted on the same graph so that their output could be compared, as shown in Fig 7. The cumulative error associated with the Dipstick data, due to foot slippage, can be noticed readily. The slippage did not occur with every rotation of the instrument but since the current Dipstick elevation depends on the previous elevation reading, any error or set of errors tends to be additive. Since the rod and level survey and the Profilometer elevations cannot be distinguished in Fig 7, a more detailed graph was plotted, as shown in Fig 8. This figure is an enlarged section of the roadway represented in Fig 7. The x-axis begins at distance 625-feet and ends at distance 675-feet. This graph indicates that the absolute profiles and the slope of all three instruments are essentially identical for the same locations on the roadway's surface.

The 970-foot roadway tested was not a concrete pavement due to the lack of local safe sections with enough length to allow the Profilometer to operate at 50 mph. Therefore, two 100-foot concrete sections were used to compare the Dipstick with Class 1 rod and level data which yielded a high correlation in the absolute profiles. The results of one of these sections can be viewed in Fig 9. Further experiments are scheduled to correlate the Dipstick, the SD Profilometer, Profilograph, and other roughness instruments on a newly constructed continuous concrete pavement identified at La Grange, Texas.

The results showed that the Dipstick is an attractive device for determining accurate smoothness data and its desirable operating and design features—light weight, portability, repeatability, accuracy and relative inexpensiveness—support further development within the draft smoothness specifications. Currently, this seems best achieved by using the California Profilograph to provide the basic smoothness data and periodically checking its output using the Dipstick. This instrument could also be used if very accurate profile data are required, for example, in serious disputes with the contractor. Having determined that the Dipstick was an excellent device for use in conjunction with the Profilograph, the research team then decided to test the McCracken Profilograph and the draft smoothness specification on some sections of newly constructed concrete highway near La Grange, Texas.

PROFILOGRAPH TESTING

A section of highway on a newly constructed and unopened by-pass near La Grange, Texas, was an ideal location for testing the McCracken California-type Profilograph and examining basic features of the draft specification. The divided highway was 34 feet wide, including shoulder width, and was paved in two passes. A 22-foot paver made one pass down the inside travel lane and the shoulder, and a 12-foot paver returned in the opposite direction. This produced a construction joint which tied the outside lane to the inside lane and shoulder. The contractor's representative and a state highway engineer confirmed that there were operational problems which had adversely affected ride quality, especially in the early stages of the work. The contractor had controlled pavement smoothness using of a 10-foot straight edge behind the paver. The texture and skid resistance were achieved using astro-turf and a machine with metal tines. The concrete was supplied in ready-mixed form, which caused additional problems with product quality. The machines were fitted with ordinary drum discharge units which could not always drop the material at the correct speed, causing the paver to stop. At other times, concrete spilled from the chutes and was not always cleaned up effectively, making the general surface of the travel lanes appear rough and uneven.

Two sections were selected for the testing: one captured the work just a few days into the contract and the other had some interesting geometric characteristics including a superelevated curve of approximately 2 degrees radius which directly joined a concrete bridge deck. In both sections, two wheelpaths within each travel lane were measured six times with the Profilograph to check its repeatability. The same operator was used on all runs in an attempt to minimize operator error. A plumb bob was attached to the extension arm to help the operator follow the same wheelpath on every run. The instrument had previously been checked for distance performance, while the calibration of the vertical displacement of the instrument was done on the job site, in accordance with draft Texas test methods (19).

The profile data sheets were stored after each run and interpreted later off-site by three research staff to check transcription errors. On actual contracts built under the proposed specifications, data will need to be interpreted at the site office and at times under less than ideal conditions. These facts were were kept in mind when the results were evaluated. A PI value for each run was calculated by counting the deviations from the 0.1-inch blanking band, and a coefficient of variation (CV) value was determined for each lane to reflect repeatability. Results using the main operator as the interpreter are given in Table 3. Two important issues are immediately obvious. First, if the proposed specifications are rigorously followed on these sections, not one lane would have qualified for unconditional acceptance and only one (A.2.) would have given the contractor a choice of actions. Secondly, there is a wide range of CV values for all lanes and almost all are poor. As a comparison, the SD 690 Profilometer had a median CV of between 0.5 and 1.5 (depending on roughness statistic) when being tested for Arizona's smoothness specification (6, 20).

Lane 1 was constructed at the very early stages of the project and shows a high PI value for both wheelpaths. Although there was some concern that the distance measuring mechanism may not have been working properly on this particular lane, the values are still high enough to cause severe problems for any contractor attempting to grind down the profile to acceptable levels. The Profilograph has the merit of giving a physical profile that the state engineering and contracting staff can study, interpret, and inspect on the work site. Generally, serious defects are accurately sighted on the travelway, together with other design features, such as the deck joint on section B, which appeared as a pronounced spike, though omitted from the PI calculation, in accordance with the proposed specification.

Contractor's traffic had operated over some of the lanes and worn away some of the loose material, making these lanes appear somewhat smoother. However, theoretically the blanking band takes out these variations, so the PI values based on the Profilograph output should be similar, irrespective of the wheelpath's micro-textural condition. The rougher texture did result in more vibration of the instrument, which produced a scattered output. The interpreter reported that the blanking band did take out most of this extra roughness but that considerable discretion had to be used in determining the extent of the wavelength amplitude. This feature will be tested in future work by using a variety of staff to determine PI data from Profilograph output and comparing results.

Some data look strange, for example, wheelpath PI values vary significantly within lanes and between runs, which creates uncertainty when considering whether the Profilograph can be used alone to determine narrow incentive clauses. However, since it possesses some important virtues and appears to be extremely effective in getting smoothness quality up to acceptable standards, using it in conjunction with a Class 1 profiling device such as the Dipstick has considerable merit and is now considered.

CONCLUSIONS

Pavement smoothness is one of the key elements considered by highway engineers when deciding the level of quality achieved on specific pavement work. Quality control is complex and sometimes paradoxical, so efforts to improve construction standards have to be carefully analyzed. The evaluation of the Profilograph provides a good example of the types of problems encountered in such analyses. The instrument did not perform particularly well in initial CTR testing, especially where its repeatability was being evaluated. Research staff tried to identify the source of this problem by examining three issues; calibration routines, operational features, and data transcription routines. The findings were:

1. the device met all existing calibration requirements adequately. In the static vertical displacement tests it was extremely accurate and also met its distance measuring standards.
2. Dynamic tests showed that the instrument is difficult to operate consistently, and that trying to keep it at a constant speed over 528 feet is challenging, particularly on curves. It is also extremely difficult to follow the same path when making repeat runs, because the bicycle wheel has such a narrow cross-section. This could be an important source of output variance.
3. When transcribing the data, the blanking band position can give rise to different PI values, and this is currently being investigated by employing a number of staff to reduce the same data to derive PI values, and then compare results.

It is hoped that CTR staff can identify the key issues, write modified operating instructions, and improve the consistency of the Profilograph output.

The evidence from other states using this device is that it is effective for day to day quality control, although this may have little to do with its absolute performance as a profiling device. If contractors are aware that state engineers are checking quality, they may take steps to ensure that their crews attain higher work standards. However, the Profilograph does record imperfections that contract staff can locate on the pavement surface, and can also be used to great effect in the early days of a contract to assist in the setting of paving equipment and training of operatives. The real difficulty with the device appears to be in the measurement of the finished profile for incentive purposes where the issues of variability and repeatability might prejudice its effectiveness.

The merits of the Profilograph at the moment outweigh its disadvantages, but its use requires that the guide specification be re-written to simplify the conditional category and change the bonus and conditional penalty clauses from a stepped format to a continuous function. Problems encountered when using a Profilograph could be avoided by employing a higher classification profiling device in conjunction with this instrument. The Dipstick seems capable of meeting this need and more tests are scheduled to decide how this influence can be effectively implemented. One possibility, for example, is to use the Profilograph to assist the contractor during construction, and the Dipstick to assess the final product profile for acceptance standard and incentive schemes.

More tests on the concrete sections already surveyed by the California-type Profilograph are scheduled, using two Dipsticks, an SD 690 Profilometer and other Texas SDHPT roughness devices. This will allow comparisons between instruments and permit further investigation of the performance of the Profilograph. If agreement is reached on the joint use of Dipstick and Profilograph, software changes to the Dipstick will be made to either allow a PI numeric to be calculated or a conversion developed to change PI into equivalent international roughness index (IRI) data (15). Such changes could be in the form of down loading to a lap top computer and using windows to report alternative roughness units and profile characteristics.

Finally, the Dipstick could be used to great effect on highway sections where the California-type Profilograph is not particularly suitable as an acceptance device, such as ramps, service roads, bridge deck transitions, and superelevated curves. The 10-foot straight edge now seems to have a very limited application in the efforts to improve pavement smoothness quality while rod and level surveys are too expensive and slow. Dynamic devices are promising but are presently too heavy for newly constructed pavements and awkward to work with in terms of contractor and highway engineer efficiency. Currently, the combination of California-type Profilograph and Dipstick seems a very effective solution to the problem and this will be pursued in the future CTR testing program for the Texas SDHPT.

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TABLE 1. SYSTEM OF ROUGHNESS BONUSES AND PENALTIES

PROFILE DEVIATION IN/MI	PROFILE ACCEPTABLE	RECTIFICATION REQUIRED	ADJUSTED UNIT PRICE MULTIPLIER
0-3	YES	NO	1.05
>3-5	YES	NO	1.03
>5-7	YES	NO	1.01
>7-10	YES	NO	1.00
>10-15	NO	YES	1.00
>10-11	YES	NO[1]	.98
>11-12	YES	NO[1]	.96
>12-13	YES	NO[1]	.94
>13-14	YES	NO[1]	.92
>14-15	YES	NO[1]	.90
>15	NO	YES, TO 10 OR LESS	1.00

[1]Contractor chooses between no rectification and adjusted unit price penalty or rectification back to 10-inches or less for full unit price.

TABLE 2. A CLASSIFICATION OF PROFILING INSTRUMENTS

CLASS	METHOD	MAX. ERROR	MEASUREMENT INTERVAL	EXAMPLE INSTRUMENTS	COMMENTS
I PRECISION PROFILES	MANUAL ABSOLUTE ELEVATION RELATIVE TO TRUE HORIZONTAL	1.5% BIAS; 19 INCH/MILE	LESS THAN OR EQUAL TO 1 FOOT	ROD & LEVEL DIPSTICK TRRL BEAM	DATA COLLECTED MANUALLY AND PROCESSED TO GIVE ROUGHNESS STATISTIC; VERY ACURATE BUT LABORIOUS AND SLOW
II DIRECT PROFILING MEASUREMENT	ELECTRONICALLY MEASURED ELEVATION PROFILE FROM ARTIFICIAL "HORIZONTAL" DATUM	5% BIAS; 44 INCH/MILE	LESS THAN OR EQUAL TO 2 FEET	GM PROFILOMETER K.J. LAW PROFILOMETER TEXAS PROFILOMETER FRENCH APL	DATA COLLECTED FROM MOVING VEHICLE; DIFFER IN REFERENCE USED AND METHOD OF SENSING; NOT ABSOLUTE PROFILE BECAUSE OF LACK OF LOW FREQUENCY RESPONSE; CAN BE UTILIZED FOR CALIBRATION
III A RTRRMS	MEASURE DYNAMIC RESPONSE OF A MECHANICAL DEVICE TO ROADWAY SURFACE	10% BIAS; 32-63 INCHES/MILE	CONTINUOUS OVER TEST SECTION LENGTH	MAYS RIDE METERS ARAN BPR ROUGHMETER DYNATEST 5000 RDM COX ROADMETER	MOST COMMON INSTRUMENTS; (1) MEASURE OF AXLE-BODY MOVEMENTS USUALLY SUMMED TO GIVE CUMULATIVE "BUMPS" PER UNIT DISTANCE, OR (2) MEASURES ACCELERATIONS OF AXLE OR BODY VIA ACCELEROMETERS; DATA COLLECTED AT HIGHWAY SPEEDS; REQUIRES CALIBRATION
III B MOVING DATUM PROFILES	MEASURE DEVIATION OF PROFILE RELATIVE TO A DATUM MOVED ALONG ROAD SURFACE	BLANKING BANDS USED TO FILTER OUT CONSTRUCTION TECHNIQUES SUCH AS TINING	CONTINUOUS OVER TEST SECTION LENGTH	ROLLING STRAIGHT EDGE SLIDING STRAIGHTEDGE PROFILOGRAPHS	INSENSITIVE TO WAVELENGTHS EQUAL TO INSTRUMENT BASELENGTH, PROFILOGRAPH AVERAGES END REFERENCE POINTS; SIGNAL GAIN HIGHLY TUNED AND VARIABLE (IDEAL IS UNIFORM GAIN)
IV	SUBJECTIVE ESTIMATES MADE BY OBSERVER(S) USING A DESCRIPTIVE SCALE				NOT SUITABLE FOR COLLECTING ROUGHNESS DATA FOR HPMS

TABLE 3. PROFILOGRAPH PI OUTPUT FROM CRCP HIGHWAY SECTIONS

SECTION		A				B			
LANE		1		2		1		2	
WHEELPATH		1	2	1	2	1	2	1	2
RUN	1	27.3	24.6	21.1	11.9	23.1	15.1	30.5	11.6
	2	25.5	30.8	19.4	9.7	19.6	16.1	27.7	10.5
	3	31.7	29.0	21.1	9.7	21.7	15.4	27.3	10.5
	4	29.5	28.2	19.4	8.8	19.6	17.9	26.2	10.2
	5	29.9	28.6	16.7	11.0	20.3	19.3	30.5	10.9
	6	29.5	22.4	18.0	11.0	20.7	16.5	29.8	10.5
AVERAGE PI		28.9	27.3	19.3	10.3	20.8	31.0	28.6	10.7
C.V.		7.1	12.0	6.3	12.3	6.4	8.2	7.0	4.3
AVERAGE PER LANE		28.1		14.8		25.9		19.7	

Fig 1. Graphical representation of proposed specification for incentive payments.

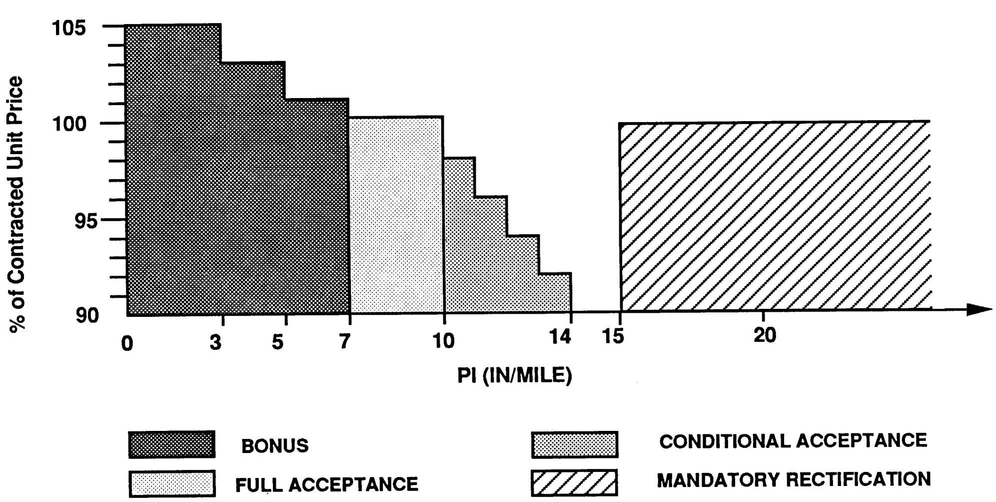

Fig 2. Continuous function fitted through bonus and acceptance PI ratings from Fig 1.

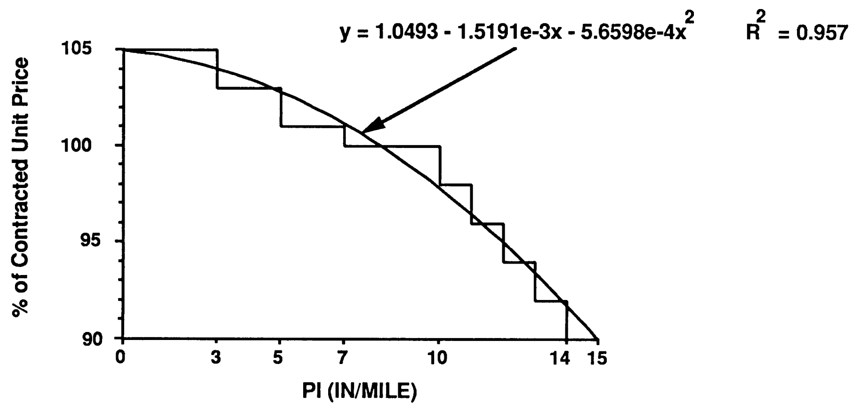

Fig 3. McCracken Californian profilograph.

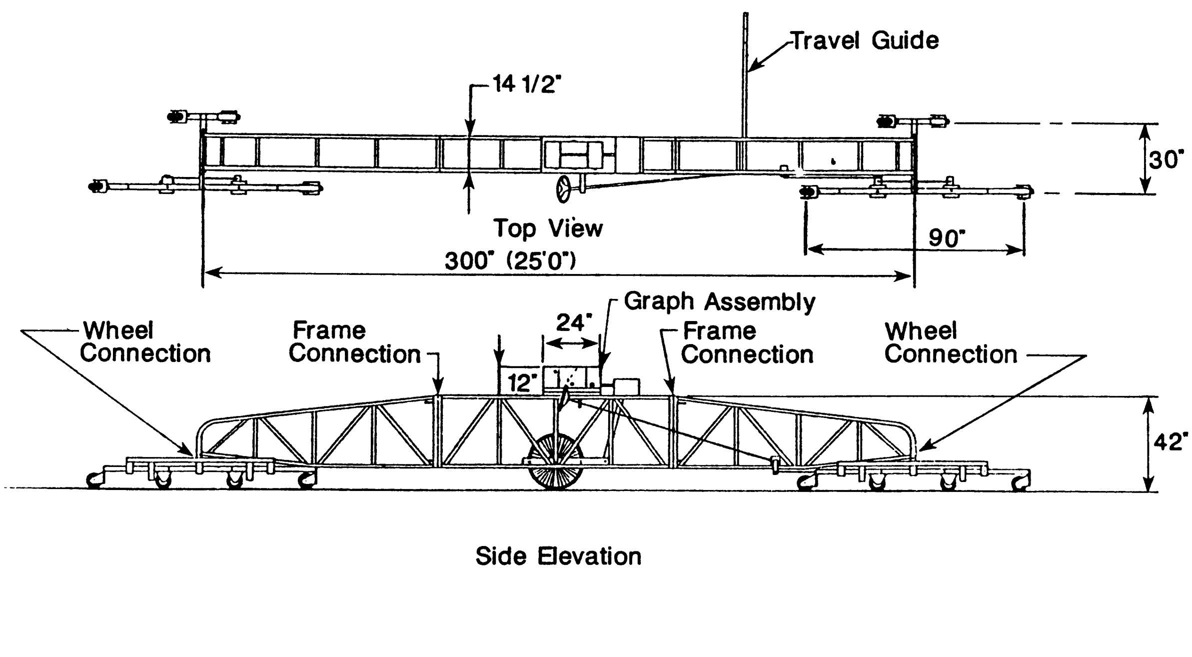

Fig 4. Face Dipstick.

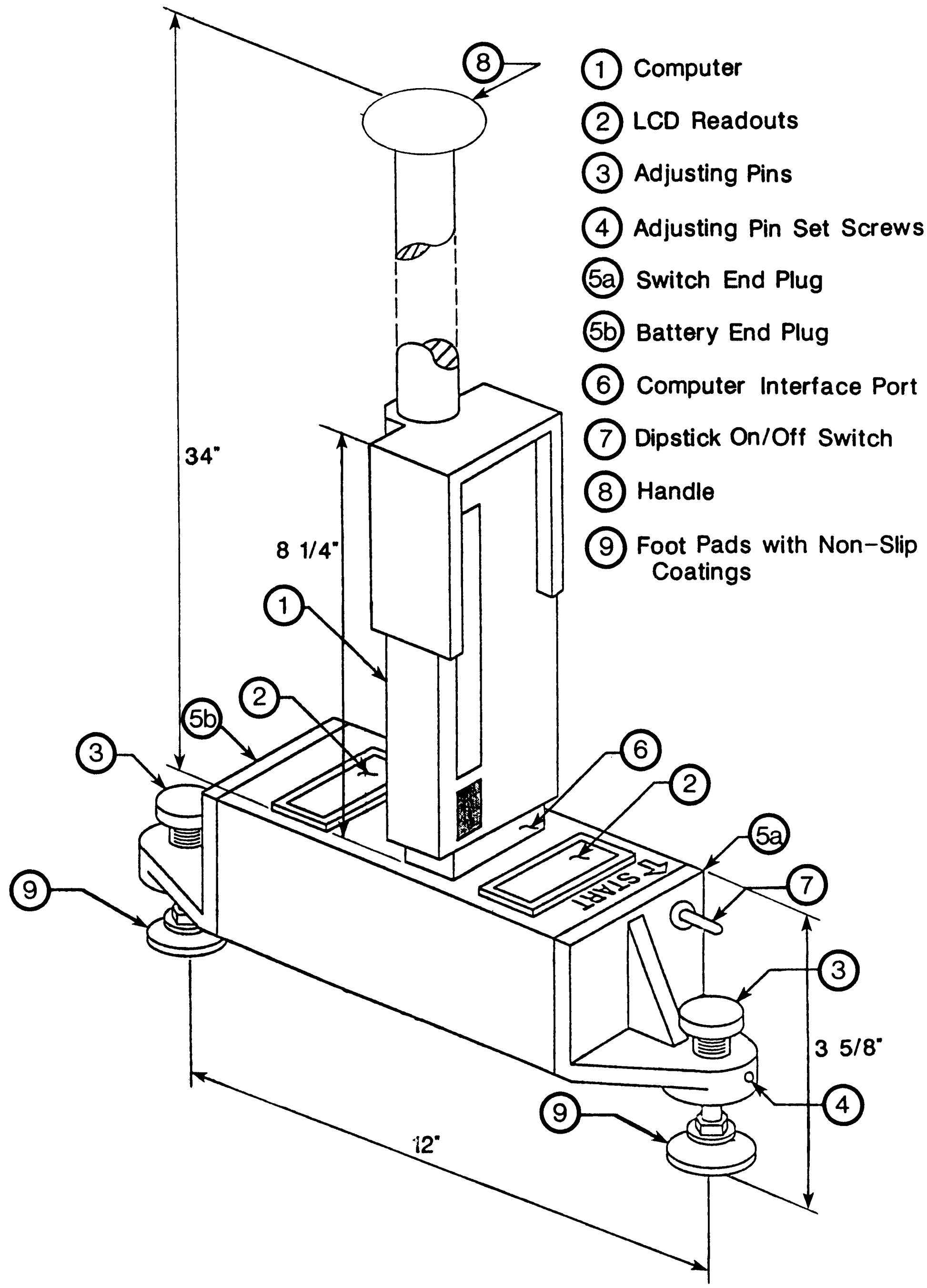

Fig 5. Dipstick repeatability determination.

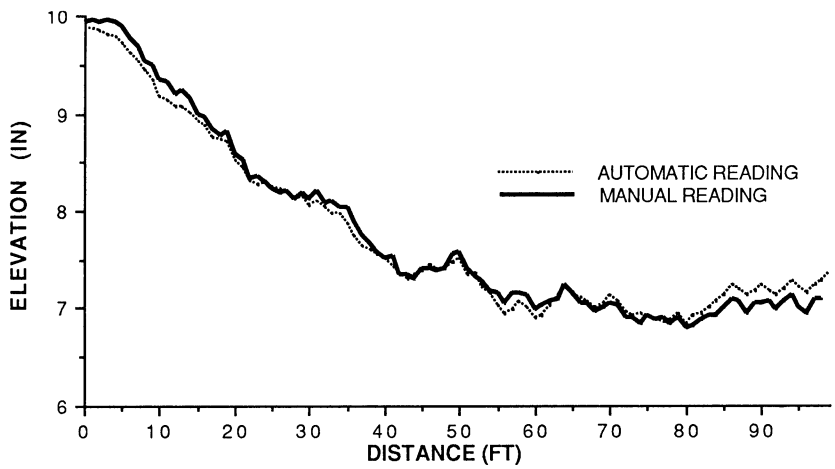

Fig 6. Dipstick operator error determination.

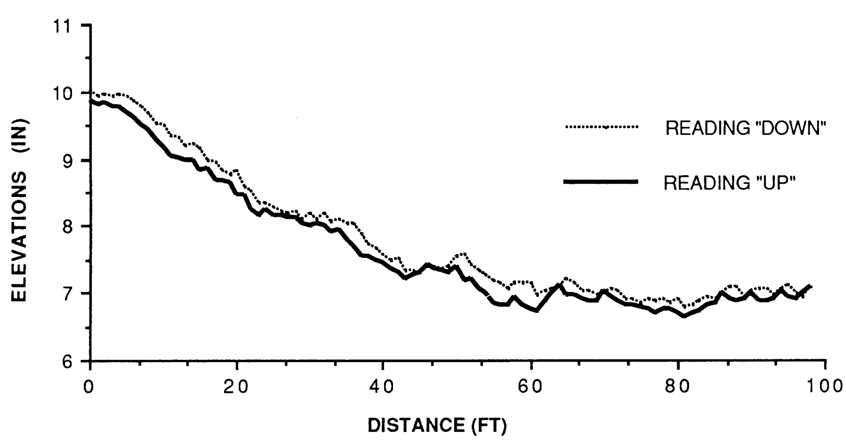

Fig 7. Comparison of profiling instruments.

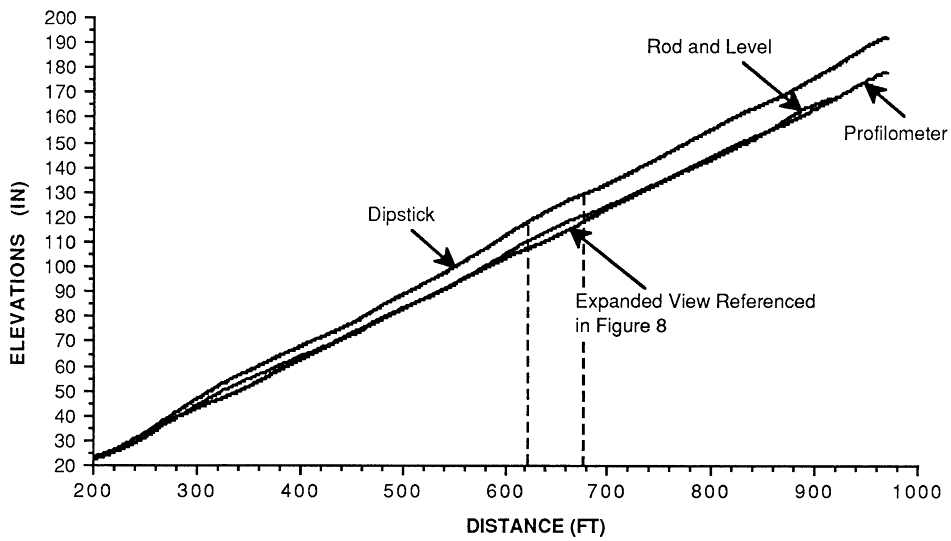

Fig 8. Exploded view of a section of the comparison of profiling instruments.

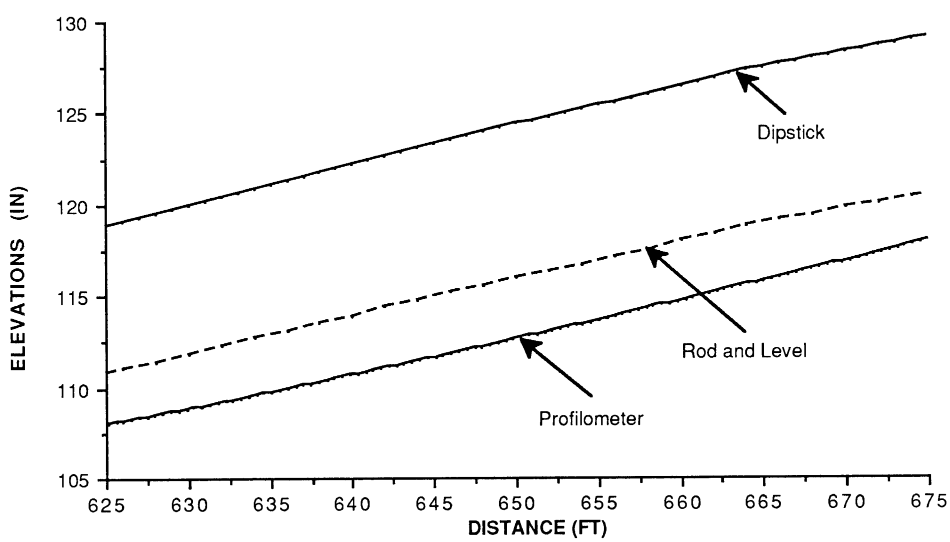

Fig 9. Comparison of the Dipstick and rod and level on a section of concrete pavement.