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EQUIPMENT AND STANDARD FOR ROADWAY CONSTRUCTION ACCEPTANCE BASED ON SMOOTHNESS

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16. Abstract

This study deals with a method for testing smoothness of pavement (both rigid and flexible) for construction acceptance. A multi-wheel profilometer is evaluated for its ability to accurately measure roadway smoothness. Measurement results were correlated with simulated response of other type of smoothness meters based on an absolute survey of road profile. The multi-wheel profilograph is recommended for acceptance of pavement based on smoothness.

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I. INTRODUCTION

The Colorado Department of Highways established the requirement that roadway pavement construction must be (in addition to all other specifications) accepted based on smoothness. Presently, this requirement has not been enforced because a practical method is not readily available. The current Colorado specification for surface tolerances states "The variation between any two contacts with the surface shall not exceed 3/16 inch in 10 feet. All humps and depressions exceeding the specified tolerances shall be corrected by removing defective work and replacing it with new material as directed". Historically, concrete pavements have been brought into tolerance by grinding. Asphalt pavements, however, do not lend themselves to grinding, and often removal and patching causes rougher riding pavements than the initial condition. Additionally, no price adjustment formulas accompany this specification, so new pavements of marginal smoothness have often been accepted at full price while corrective action was only taken on extremely rough asphalt surfaces.

This report is intended to help in the adoption of a meaningful specification and test procedure acceptable to both highway and contractor personnel to assure pavement smoothness. Adoption of specifications and equipment showing the degree and location of non-compliance of roadway smoothness would greatly aid field personnel in directing corrective action and determining price adjustments for substandard pavement smoothness. This action would help ensure better quality roadways for the traveling public.

This test procedure should apply to overlay projects in addition to new construction and, therefore, help assure the quality of a large portion of highway construction activity.

The study consists of:

1. selecting the most appropriate test equipment
2. acquiring selected equipment and evaluating its performance
3. determining the relationship of the statistic generated by the selected device with familiar roughness devices
4. determining the recommended standard and test procedure for pavement acceptance

After a review of available methods and equipment for measuring roadway smoothness the Rainhardt profilograph was selected to be evaluated. Following the purchase of this equipment, three calibration test sites were selected and their smoothness evaluated using three methods. The first method utilized a survey rod and level. The second utilized Colorado's skid truck profilometer. The third method utilized the profilograph purchased.

II. EQUIPMENT ALTERNATIVES

The first step in this study was to determine the best equipment for the job. It was decided that the equipment as a minimum should:

1. provide a visual indication of profile
2. generate a profile statistic (i.e., inch/mile, slope variance, etc.)
3. reference frame should span over at least 10 feet
4. be reliable and easy to maintain
5. be easy to operate
6. be easily transported
7. operate accurately over a broad temperature range
8. accurately measure roughness especially for smoother roads

Some optional capabilities could be:

(1) sample profile over a wide area

(2) mark location of high and low pavement deviations

(3) operate at highway speeds

Numerous types of off-the-shelf equipment are available for measuring roadway smoothness. Each general type was considered for pavement acceptance testing. These systems are described below along with their advantages and disadvantages.

A. Straightedge and Ruler

A measurement of roadway smoothness can be accomplished without specialized equipment. A string line and ruler or a rigid straightedge and ruler can be used to accomplish this task. The resulting measurements can then be compared to the current Colorado Standard of 3/16 inch in 10 feet. If extensive measurements are taken, a smoothness statistic can be computed for price adjustments or corrective actions. Extreme deviation can be marked for corrective action by the contractor. The advantages of this method is the absence of capital expenditures and its simplicity. The tester can readily demonstrate that a particular location exceeds the specifications. The disadvantages of this system are the enormous time required for comprehensive testing and the extensive opportunity for human error.

B. Rolling Straightedge

One step beyond the straightedge and ruler is the rolling straightedge which allows continuous measurement of roadway smoothness. A rolling straightedge is usually comprised of a 10-foot long rigid beam supported on both ends by wheels. In the center is a sensing wheel linked to an indicator dial which shows deviations from a level road. Options are available which activate a spray paint when indications fall out of tolerance. The paint marks the roadway for later corrective action. These machines do not generate a roughness statistic or a graph of the profile. A triple counting of severe bumps can be indicated as each support wheel passes over a bump. The machine is easy to operate and transport and relatively low in cost. This is the major reason for its widespread use for pavement smoothness acceptance.

California uses a modified rolling straightedge for their roadway acceptance instrument. The machine is a rolling straightedge with a strip chart recorder mounted to it. A smoothness statistics is created from this test by manually evaluating the chart produced. Vertical variations that migrate beyond a 0.1 inch dead band are accumulated and a profile index determined. The complete California method is shown in Appendix D.

C. CHLOE Profilometer

The CHLOE profilometer holds a historical significance, rather than a present method of pavement smoothness testing. The CHLOE was developed in the early sixties in conjunction with a roadway evaluation study to establish the Pavement Surfaceability Index (PSI). An equation was developed which correlated the statistic generated by CHLOE with the general public's perception of road condition. The perceived condition of the road is the Pavement Surfaceability Index (PSI) and the CHLOE statistic is the slope variance (SV).

The CHLOE measures the difference in slope between the 25-foot trailer and a pair of sensing wheels 9 inches apart. This difference is sampled every 6 inches of travel and a statistical variance of the data is computed. Because of the dynamics of the system, operating speed is limited to 2 to 3 mph. The CHLOE also has no capability to indicate locations of excessive roughness within a test section.

D. Response Type Roadway Roughness Meters (RTRRM)

RTRRMs measure the response of a vehicle to the roughness of a road. Typically, the statistic generated is established by monitoring the movement of an axle. Three common devices are the PCA meter, BPR roughometer and the Mayes ride meter. In addition to these the Colorado skid truck bumpmeter will be discussed.

PCA Meter. The PCA meter, originally developed by the Portland Cement Association, accummulates movement of a rear axle with respect to a car body. The total count is weighted according to how far the axle deviates from the neutral position. The statistic generated effectively has units of square inch/mile so correlation with the usual in./mi. statistic results in a quadratic relationship.

BPR Roughometer. The BPR roughometer, originally developed by the U.S. Bureau of Public Roads measures movement of a trailer axle. The register accumulates inches of vertical axle travel in one direction. From this an inch/mile statistic is computed. Response of this system is somewhat different than one based on a car axle because of the smaller mass of the trailer.

Mayes Ride Meter. The Mayes Ride Meter is probably the most widely used RTRRM. It measures the movement of the rear axle of a car with respect to the chassis to obtain inch/mile of vertical movement of the axle. Recently, a trailer based Mayes meter has been marketed. The trailer has the weight and the suspension system similar to a passenger car. The trailer provides a standard suspension system which can be held constant over many years in spite of the regular replacement of the towing vehicle.

Both Florida and Georgia use a trailer-based Mayes meter for acceptance of asphalt paving. South Carolina uses the Mayes meter for screening new pavement while final rejection is based on a rolling straightedge.

Skid Truck Bumpmeter. The skid truck bumpmeter is used exclusively by the Colorado Highway Department for statewide inventory. This device measures the change in the angle between the skid trailer chassis and the towing truck chassis. The variance of this angle is then determined using an analog computer. Response of this system has been compared to that of the CHLOE profilometer over a wide range of pavements and a relationship was established between signal variance and PSI. Aside from the usual problems that threaten the accuracy of RTRRM systems, which will be discussed below, the skid trailer based system has its own unique problem. First, out-of-roundness of the locking skid tire could introduce artificial roughness. Next, although the majority of the response is expected to be from the action of the trailer itself, varying loads in the truck could change the response. The load in the truck does indeed vary dramatically as water in the tank is consumed during skid testing. Finally, vertical curves can have an excessive affect on the result because of the long base from which the angle is measured.

RTRRM Problems. All RTRRMs have common problems which affect their accuracy. First, for a vehicle based system, changes in the load in the vehicle will change its response. Next, replacement of the vehicle will change the response and extensive correlation tests must be conducted every time a vehicle change over is performed in order to maintain continuity in the test results.

For all RTRRM systems, tire imbalance and out-of-roundness can introduce artificial roughness into the measurement. Further, changes in tire pressure, ambient temperature, and vehicle loading can change the response of the system to a particular road. Tire pressure changes alter the spring coefficient of the tires while ambient temperature affects the damping coefficients of the shock absorbers and tires. The magnitude of these effects are different for different roadways. Statistics from roadways with long wave length bumps will be more sensitive to ambient temperature changes while statistics from roadways with short wave length bumps will be more sensitive to tire pressure. Long term errors can result from wearing of the suspension system, components, and replacement with different styles or brands of tires.

E. Inertial High Speed Profilometer

A system was developed by General Motors to measure absolute profile of roadways at highway speeds. The system is a spinoff from the inertial guidance system technology developed for missiles and is commonly referred to as the GMR profilometer. This system measures the displacement of a small following wheel with respect to the chassis of a vehicle. By double integrating the signal from an accelerometer mounted on the vehicle, the absolute vertical displacement of the vehicle can be determined. Then by deducting the absolute vehicle displacement from the relative displacement of the following wheel the absolute profile of the roadway can be determined.

This device is being manufactured and marketed under licensing agreement from GMC by K.J. Law Engineers, Inc. Because of the nature of the system, complex electronics are required and system costs are well over $200,000. Also, because of this complexity, proper operation requires a great deal of training and experience. The following wheel is also a critical component. The wheel wears out quickly and can be destroyed by a pothole.

With the recent development of microelectronics and microprocessors, an internal system based on a non-contact sensing device has been developed. Although the electronics are more complicated, microcomputer technology has been used to provide a reliable system which can be operated effectively with little user training. Development of a non-contact sensor was a lengthy process and it was not until 1982 that the first system was sold. In this case, it was a retrofit for the West Virginia following wheel system. At the 1983 Annual Meeting of the TRB a downscoped system was presented. The system is based on an inertial reference and a non-contact sensor. Profile information is not stored, but a cumulative smoothness statistic is generated. The system is vehicle independent because the statistic is based on the absolute profile and computer simulation parameters instead of vehicle response. Cost of this system is between $30,000 and $40,000, however, historical evidence of in-use reliability and accuracy of a non-contact sensor have not yet been established.

III. MULTI-WHEEL PROFILOGRAPH

A multi-wheel profilograph was selected as the test equipment to be evaluated. This equipment meets all the requirements specified in Section II. The only drawback to this system is it cannot be operated at highway speeds. Operation is restricted to a walking speed.

The machine is composed of 12 wheels mounted on a frame to provide an average reference plane (see Figure 1). The profilograph has one main frame, two intermediate frames, and four wheel frames each with three wheels mounted at the points of the triangle. The main frame rests on the two intermediate frames and each intermediate frame rests on two wheel frames. The wheels are aligned so that no two wheels follow the same path. This arrangement minimizes the effect of localized bumps on the reference frame.

Mounted on the main frame is the measuring wheel which is 19 inches (48 cm) in diameter providing a 5 foot (152 cm) travel per revolution (see Figure 2). The strip chart recorder records vertical movement of the wheel with respect to the reference frame. Advancement of the chart is accomplished by a chain drive coupled to the measuring wheel. For vertical wheel movement, one inch of defection on the chart is equivalent to 1 inch on the roadway. The chart distance scale can be selected for 10 feet/inch or 25 feet/inch. The pen may be positioned to write anywhere on the chart and the chart drive can be reversed. With these features,

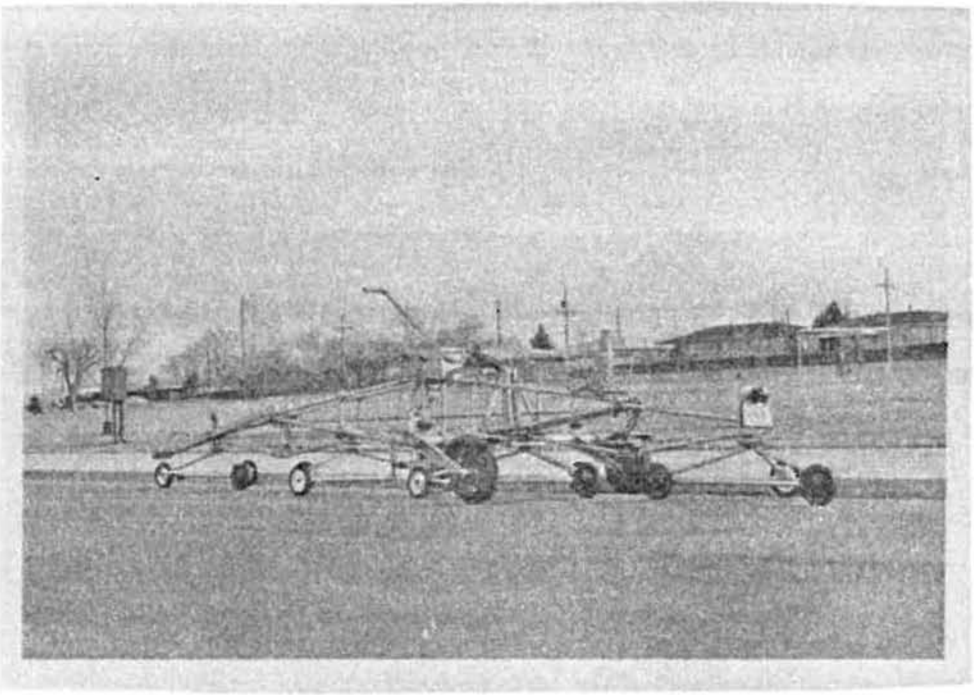


Figure 1

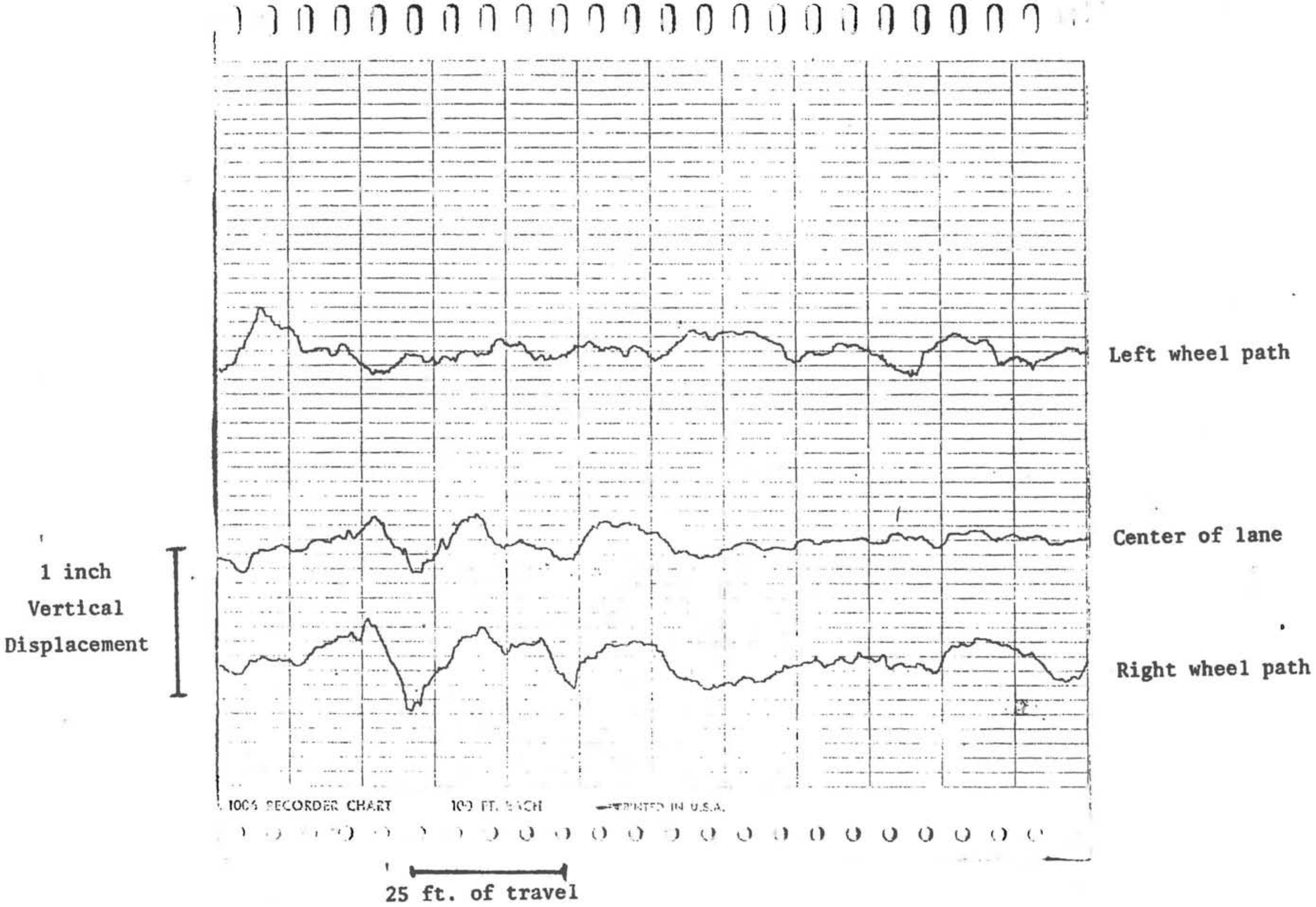
Multi-wheel
Profilograph

Figure 2
Profilograph Sensing
Wheel

slide 11

Figure 3

SAMPLE PROFILOGRAPH CHART



the left wheel path can be plotted next to the right wheel path on the chart without returning to the same starting point and resetting the chart paper (see Figure 3). One counter is coupled to the chart drive and accumulates feet of travel. Two additional counters are used to accumulate a roughness statistic. The left counter advances whenever the wheel moves down accumulating total unfiltered rectified vertical displacement. The right counter is connected through a ratchet with a 0.1 inch backlash causing only fluctuations in excess of .1 inch to be accumulated. Because of the high inertia of the wheel and linkage, the machine should not be operated faster than at a slow walk (2 mph) speed.

The frame has a standard trailer hitch and has two pneumatic trailer wheels which can be lowered into place with a lever arm. In this manner, the machine can be towed like a trailer at highway speeds.

IV. TEST PROCEDURE

Three test sections were chosen to evaluate this multi-profilograph and to correlate its results with other roughness indicators. The three roadway sections were chosen in an effort to span the range of typical roughness encountered. An absolute profile measurement was obtained with a survey rod and level. In addition, the skid truck bumpmeter and the multi-wheel profilograph were run on these three test sections.

Each test section is a flexible pavement 0.1 mile (528 ft.) long. They are located as follows:

C-470 - Eastbound shoulder west of
Santa Fe Drive
S.H. 58 - Eastbound driving lane east
of McIntyre near Golden
I-76 - Eastbound driving lane near
Barr Lake

The absolute profile was established by taking survey elevations every six inches along each wheel path of all three test sections. The survey rod used had one division every 0.01 feet and each reading interpolated between these divisions to the nearest 0.001 foot. The standard error of this process is expected to be about .002 feet. Implications of this error are discussed in the next section and in Appendix B. The survey data was coded on computer punch cards for entry into the computer.

The skid truck bumpmeter was operated over these three sections and signal variance readings were recorded. Since the skid truck bumpmeter measures both wheel paths simultaneously, no readings for individual wheel paths were possible. In addition to these three sites, skid truck bumpmeter data was collected on ten other sites in conjunction with another study, which also used profilograph data.

The profilograph was operated over each wheel path and both filtered and unfiltered statistics were collected. For the three surveyed test sections several passes were made and averaged together. Variation between each run was not great and probably was due to the inability to retrace the exact path. The ten additional sections were each one mile long and only one pass in each wheel path was made.

V. DATA ANALYSIS

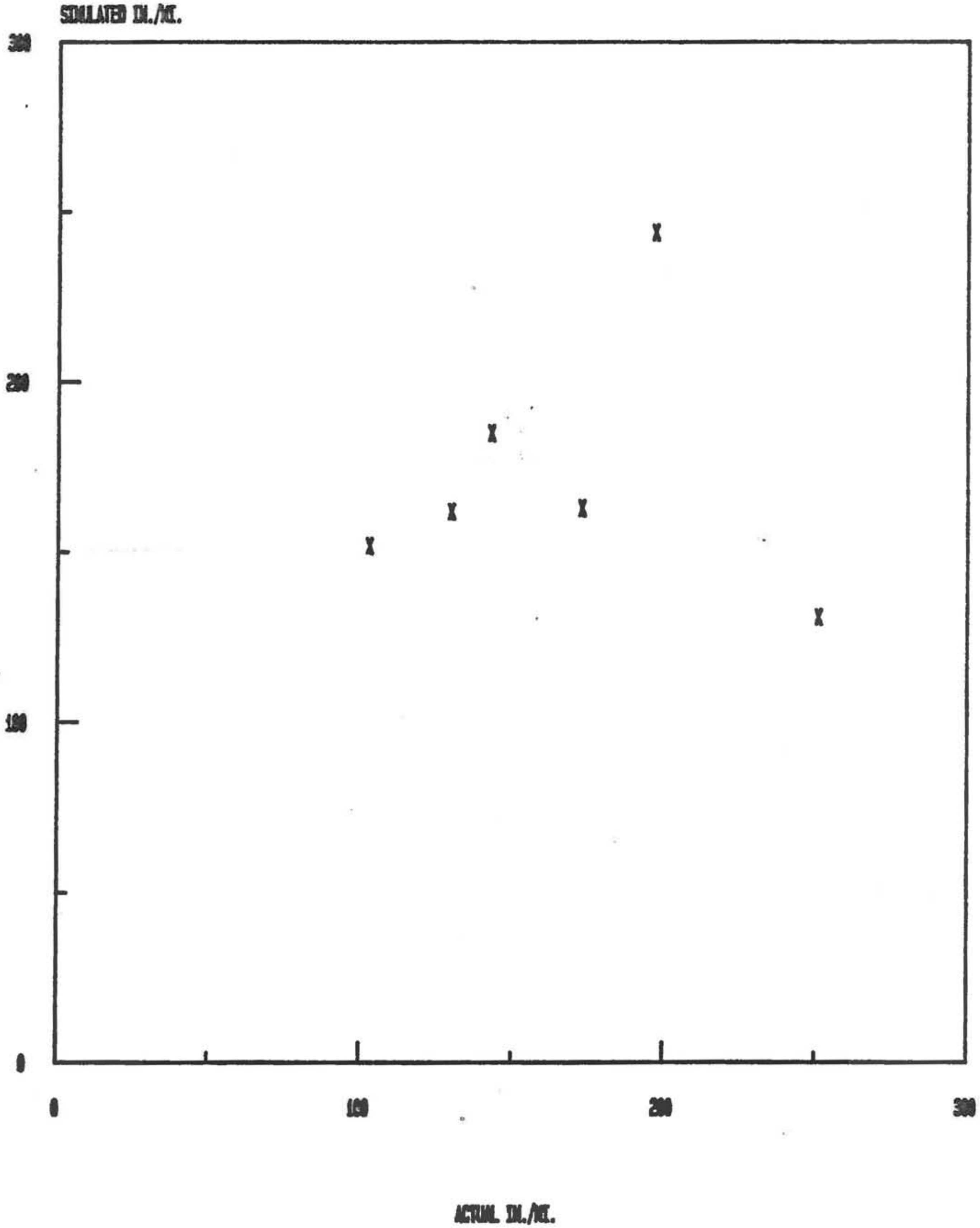
The data measured by the profilograph was compared to both the survey elevation data and the skid truck bumpmeter. The survey data could not be used directly, but had to be used to simulate the response of various other roughness meters. The signal variance produced by the skid truck bumpmeter, on the other hand, can be compared directly to the profilograph results. This comparison is discussed in subsection C.

Once the survey data was collected, program PROFIL was used to simulate the response of various roadway roughness instruments. The program can simulate the response of a CHLOE profilometer, a response type roadway roughness meter, and the multi-wheel profilograph. Results are first compared to the unfiltered statistic in subsection A and then to the filtered statistic in subsection B.

A. Comparison of the Unfiltered Statistic with Simulated Statistics

Figure 4 is a comparison of the inches per mile statistic to the same statistic which was simulated by the computer. Restated, the graph is the actual inch/mile statistic as measured by the profilograph versus the simulated inch/mile statistic. In this unfiltered statistic, even the slightest variation in the profile is accumulated. On this graph, there are six points which correspond to each wheel path for the three test sections. The poor correlation shown here is probably due to the sensitivity of the profilograph to texture and the insensitivity of the survey data to undulations shorter than 6 inches. The offset of the data (generally higher survey statistics than actual statistics) is probably due to error in the survey data and is discussed in Appendix B.

Figure 4



SIMULATED VERSUS ACTUAL PROFILOGRAPH

UNFILTERED STATISTIC

Similarly, the unfiltered profilograph statistic was plotted against the simulated CHLOE profilometer statistic (see Figure 5). The poor correlation is again due to the texture and the offset is due to survey error (see Appendix B).

Finally, the unfiltered profilograph statistic was plotted against the statistics for a Reference RTRRM (see Figure 6). The reference RTRRM was originally formulated by HSRI as a set of equations defining the response of a quarter car simulator. Specific values for the masses, spring constants, and damping coefficients were originally specified to correspond to a typical passenger car. This reference system is idealized because each car on the road will respond differently and the response of any vehicle will change as the environment changes and the components wear. Because it is an idealization, the reference can only be used as part of a computer simulation based on absolute profile measurements. This reference was proposed in NCHRP 228(1) as the universal reference for calibrating all RTRRMs. Poor correlation with the unfiltered statistics is due to its sensitivity to speed of operation of the profilograph and the fact that the profilograph measures continuously while the survey data are discrete points.

B. Comparison of Filtered Statistics with Simulated Statistics

Correlation of survey data with the filtered statistics is much better than with the unfiltered. All correlations, however, have a zero offset. That is, the best fit line through the data always passes above the origin. The offset of the survey data statistics

Figure 5

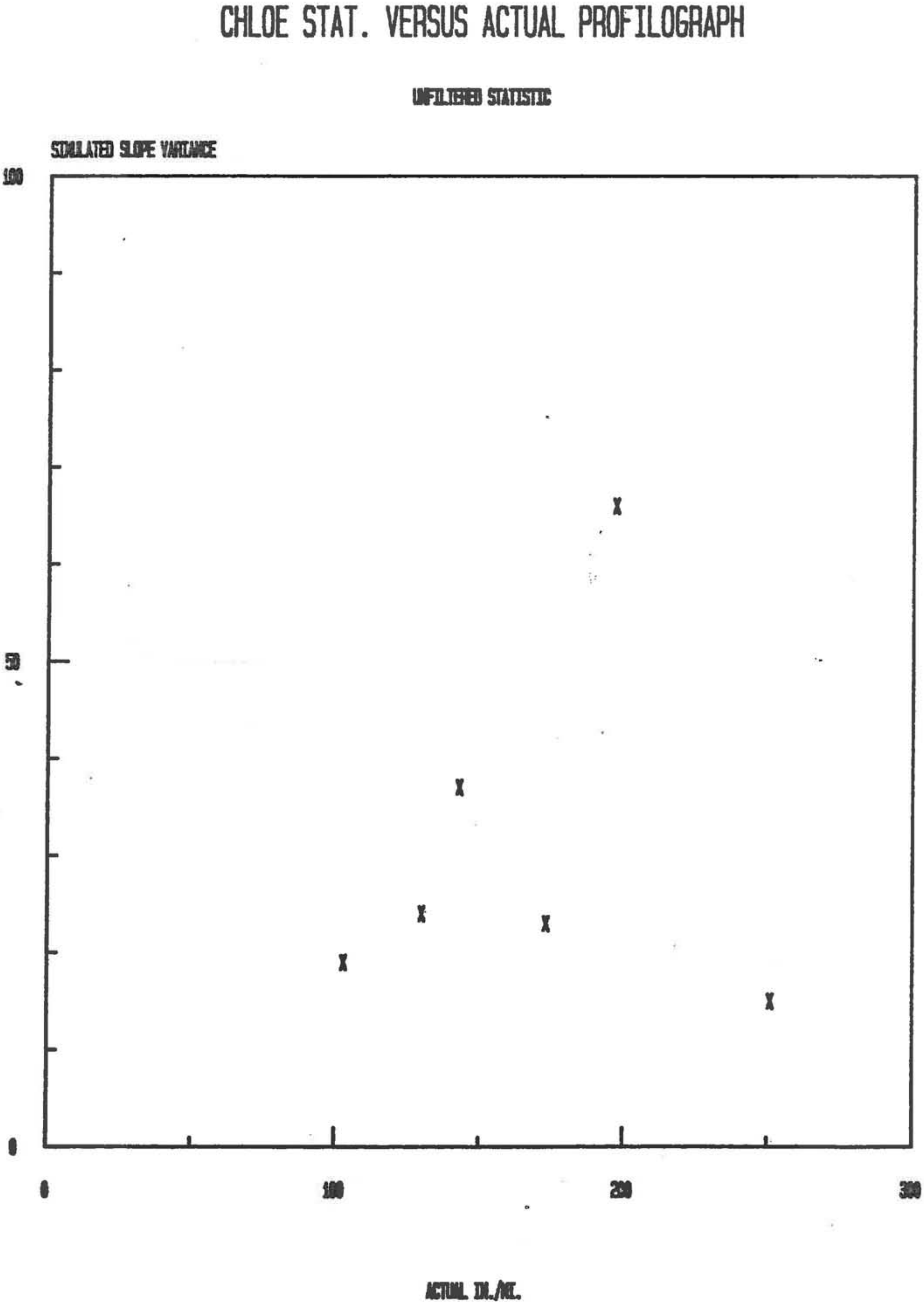

CHLOE STAT. VERSUS ACTUAL PROFILOGRAPH
UNFILTERED STATISTIC
SIMULATED SLOPE VARIANCE
100
50
0
0
100
200
300
ACTUAL IN./MI.

Figure 6

SIMUL. RTRRM VERSUS ACTUAL PROFILOGRAPH

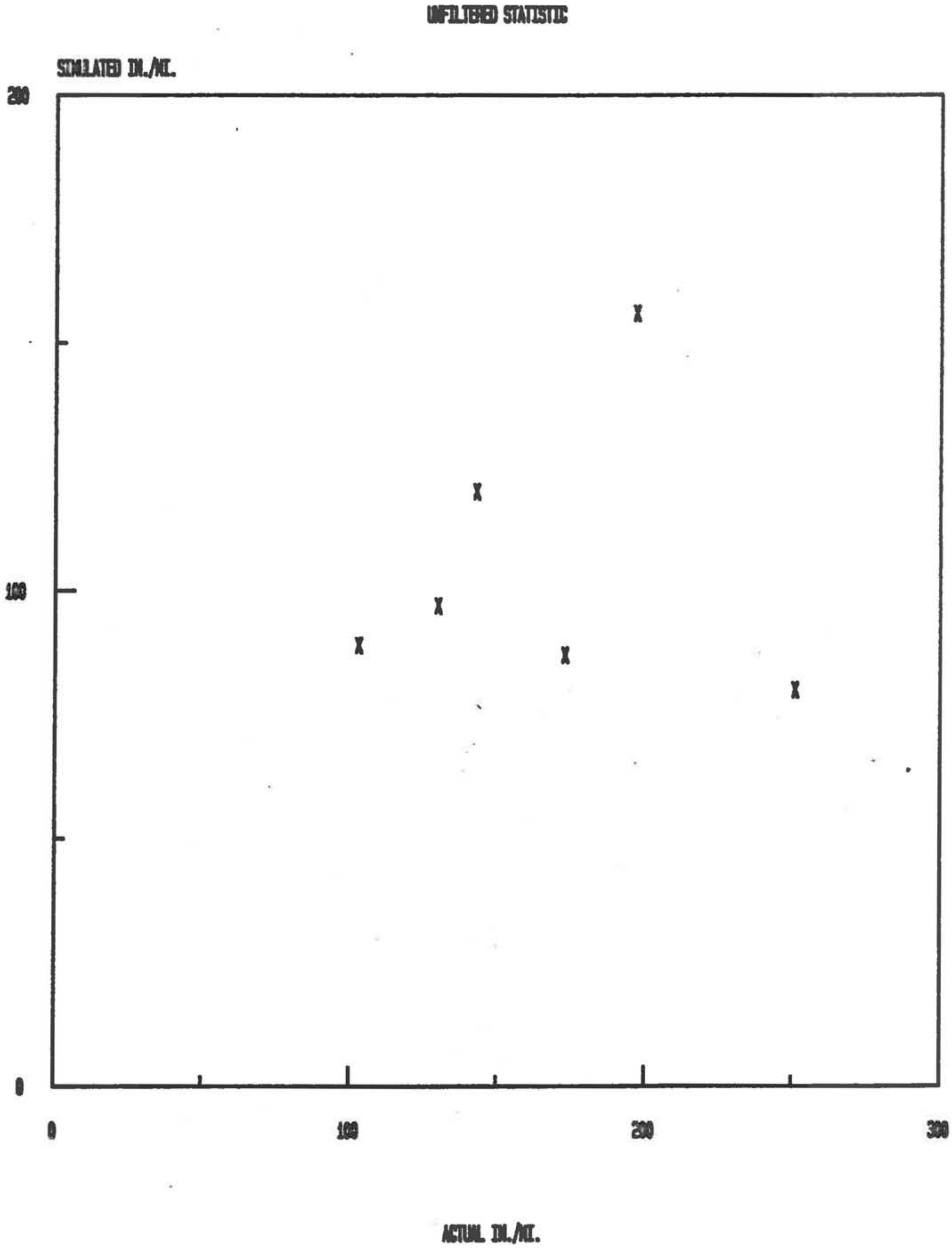
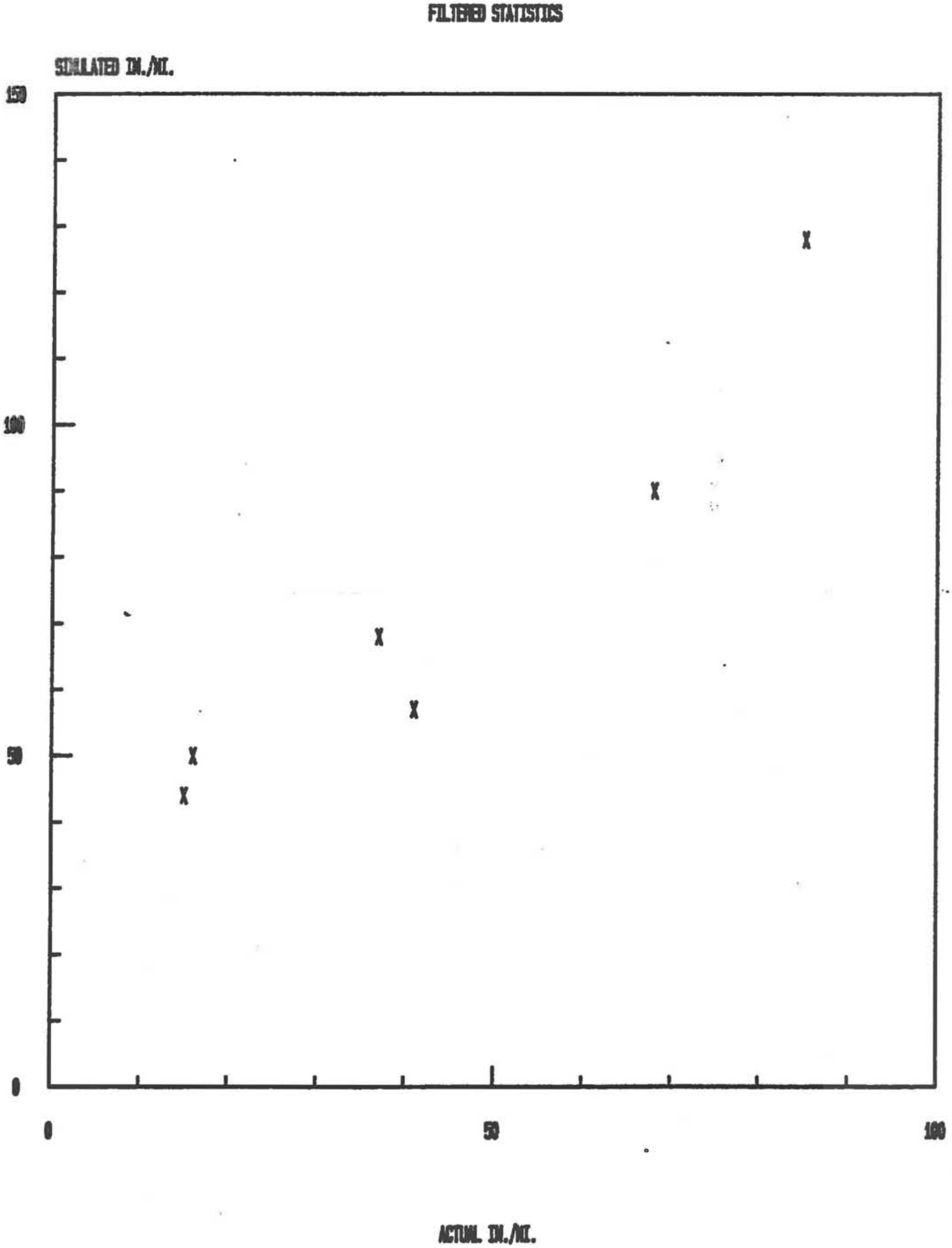


Figure 7

SIMULATED VERSUS ACTUAL PROFILOGRAPH



is due to noise in the statistics created by the expected error in the survey data. The magnitude of this offset is predicted by the Monte Carlo simulation of a perfectly flat road (see Appendix B).

The simulated filtered statistic versus the actual filter statistic is plotted on Figure 7. A best fit line of this data has a slope close to unity and an offset which is expected due to the error in the survey data. This good correlation generates good confidence for both the survey data and the profilograph. By subtracting 29 off the simulated result to account for the error offset, the actual measurement is predicted to be within a standard error of 9 inch/mile.

Similarly, good correlation is achieved with the CHLOE and RTRRM simulation (see Figures 8 and 9). Here again, the zero offset present can be explained by the noise in the survey data.

C. Comparison of Filtered Statistics with Skid Truck Statistics

Correlation of the skid truck bumpmeter data with the filtered profilograph statistics is shown on Figure 10. For this correlation not only is the data for the three surveyed sites available, but data on the ten additional sites is shown. Poor correlation is obvious and is due to many factors. Most of the possibilities for bad correlation are discussed in Section II-D. These items are things as sensitivity to temperature and vehicle loading, and out-of-round skid test tires.

Another possible cause for poor correlation could be linked to the length of the test section. The skid truck bumpmeter is oriented around roadway inventory activities which usually involve

Figure 8

CHLOE STAT. VERSUS ACTUAL PROFILOGRAPH

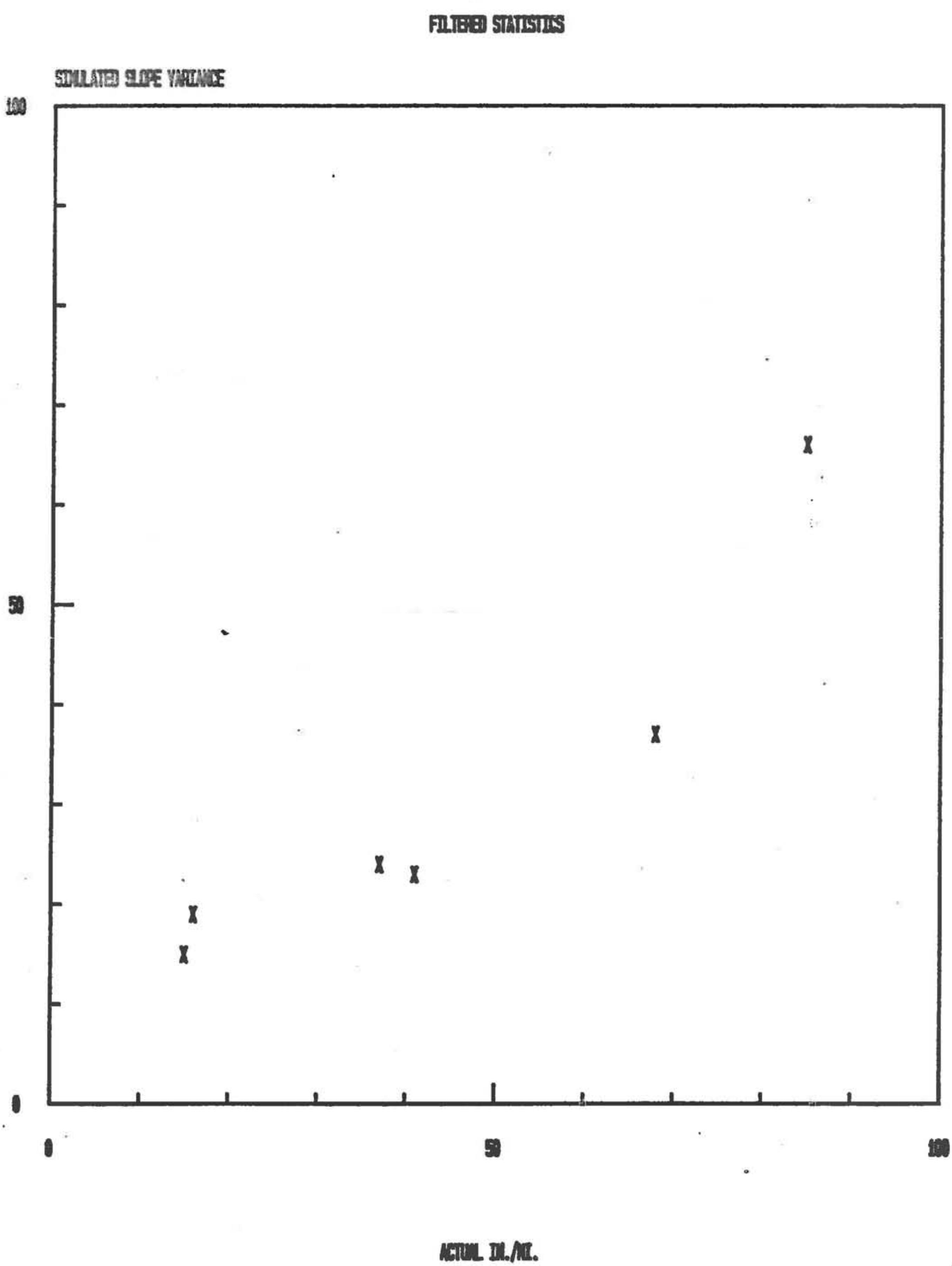


Figure 9

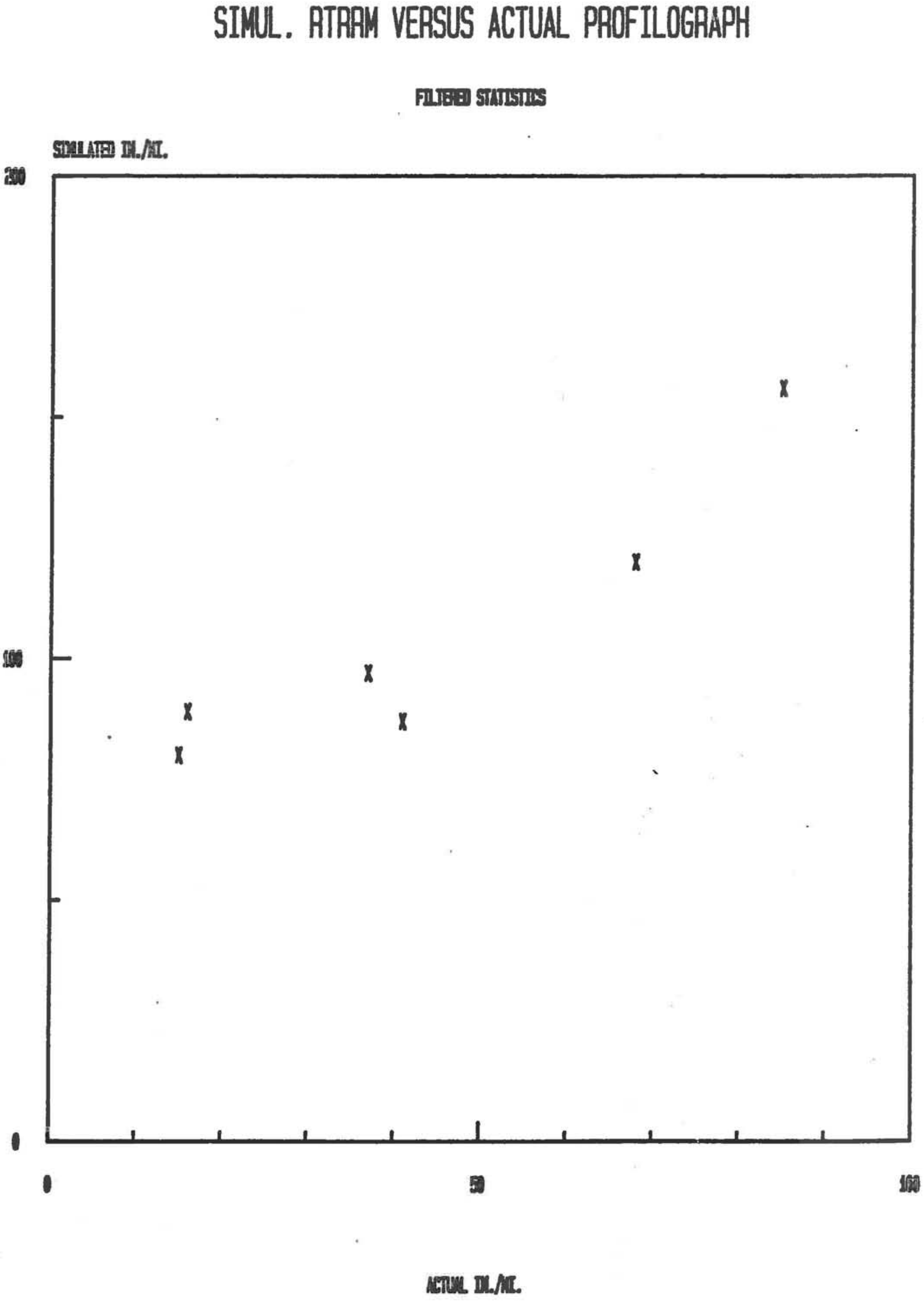
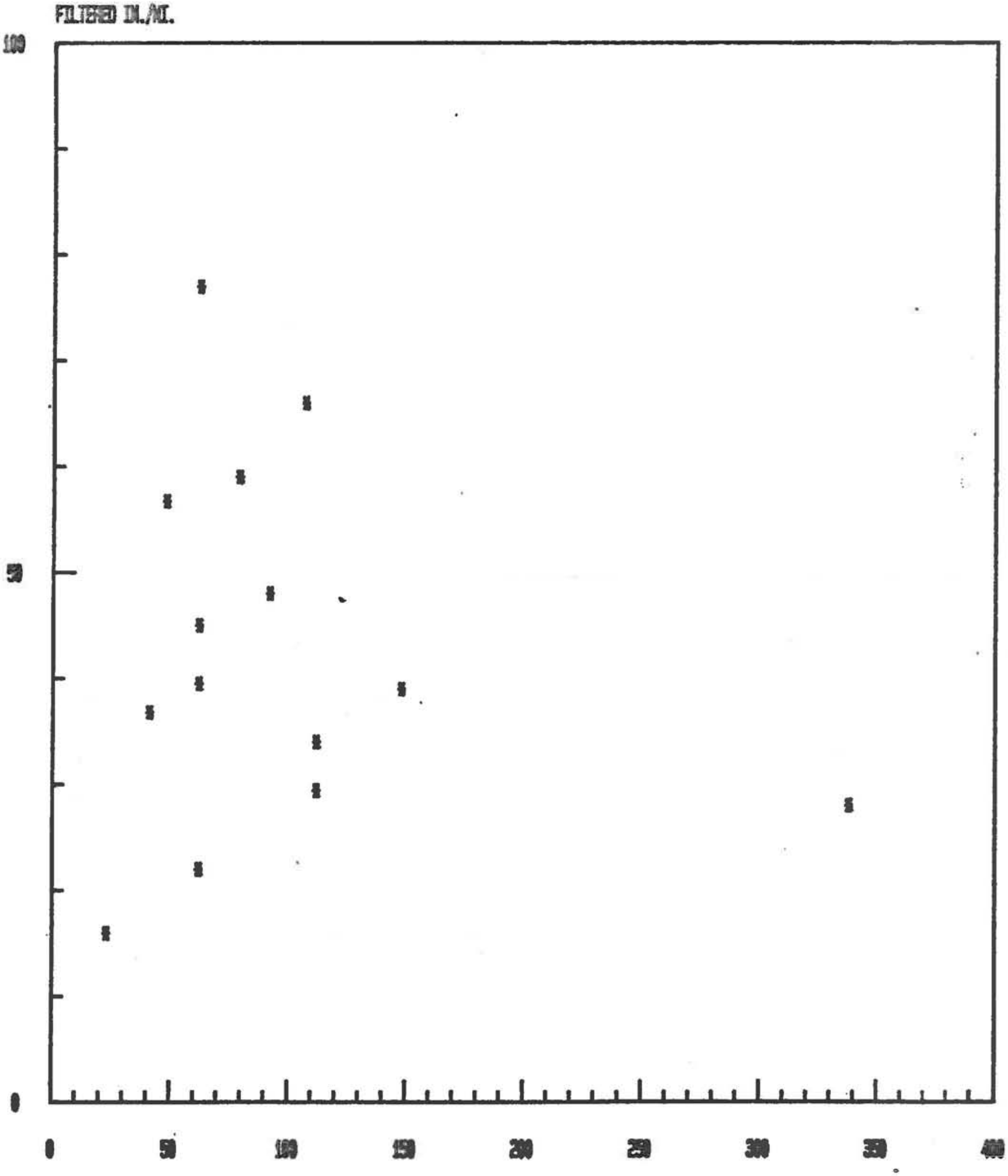

SIMUL. RTRAM VERSUS ACTUAL PROFILOGRAPH
FILTERED STATISTICS
SIMULATED IN./MI.
200
100
0
0
50
100
ACTUAL IN./MI.

Figure 10

SKID TRUCK VERSUS PROFILOGRAPH



much longer test sections. The system for averaging the signal variance is operating at the lower limit of its range when testing these 0.1 mile sections. Much uncertainty as to the behavior of the averaging system at this lower limit is present. This only can account for the problem with the three 0.1 mile sections and not the ten 1.0 mile sections. In any event, Figure 10 points out the inappropriateness of using the skid truck bumpmeter for pavement acceptance testing.

VI. CONCLUCIONS

After reviewing the equipment available for measuring roadway smoothness, it was determined that a multi-wheel profilograph is best suited for acceptance of roadway construction. This type of machine measures the profile of the road directly. Other systems considered rely on sophisticated sensors and electronics to determine an absolute profile or on the response of a vehicle to a roadway.

The only disadvantage of a multi-wheel profilograph is its slow operating speed (2 mph). This means that traffic control would be required during testing operation. However, the slow operating speed of a multi-wheel profilograph is more than offset by the machine's simplicity, accuracy, and reliability. The testing performed with this machine indicates that it accurately portrays the absolute profile of the road. The machine also correlates well with other roadway smoothness measuring devices.

The only machine available to measure absolute proflie at highway speeds is an intertial system which relies on critical accelerometers and complex electronics. Because of the complication of this system, the malfunctioning of such may not be apparent to the operator. Response type systems operate at highway speeds but are sensitive to many variables, such as amient temperature and tire condition. Also, for a response type system it is not always apparent to the contractor what type of corrective action will bring the pavement into specifications.

VII. RECOMMENDATIONS AND IMPLEMENTATION

It is recommended that the Colorado Highway Department implement an acceptance standard for smoothness based on a multi-wheel profilograph and the new proposed AASHTO specification. (The AASHTO specification is listed in Appendix C). Based on this study, the multi-wheel profilograph has been found to be a good system for measuring roadway smoothness. Since the AASHTO specification is also based on a multi-wheel profilograph, adopting this specification would provide continuity between other states without deviating significantly from our method.

During this study, AASHTO has been developing its own specification for roadway smoothness. The AASHTO specification ranges from 10 to 15 inch/mile. Roads smoother than 10 inch/mile initiate a 5% bonus while roads rougher than 15 inch/mile will require mandatory corrective action. Between 12 and 15 inch/mile, a price adjustment formula would apply (see Appendix C). The 15 inch/mile rejection would apply to each 0.1 mile segment of pavement while the price adjustment formula would apply to the overall average.

The AASHTO statistic used is based on a manual filtering process. This involves examining the actual graph produced by the profilograph and counting profile which deviates outside a 0.2 inch dead band width. This statistic can be closely approximated by using a 0.2 inch filter on one of the vertical counters. It is recommended that the unfiltered counter on the machine be replaced with a 0.2 inch filtered counter.

The specification should be implemented for both new roadways of flexible and rigid pavement. For asphalt overlays, two possibilities exist. One option is that projects with less than 4 inches nominal cover could be exempt from the specification. The second option could be to take profilograph readings before an overlay and require the contractor to reduce the inch/mile statistic by 50% for each 2 inch nominal lift down to a minimum of the specification for a new pavement.

Testing should be performed on each wheel path because this is what the public will feel. Continuous sampling of each wheel path for the entire project is recommended with the statistic recorded every 0.1 miles. The 15 inch/mile rejection should be applied on every 0.1 mile subsection while the price adjustment formula should apply to the average for the entire project. Bonus payments should not be allowed for new asphalt.

Implementation should be gradual to familiarize both the contractors and testers with the new procedure. For one paving season, acceptance testing should be performed based on 0.2 inch filter and reported on a trial basis, but no price adjustment should be imposed. Barring significant problems, full implementation should begin during the following paving season.

A future possibility is to use an inertial high speed profilometer with a non-contact sensor for asphalt pavement acceptance. Such a system would dramatically increase the test speed and eliminate the need for traffic control during testing.

A system of this type which generates a single selected smoothness statistic is available for $35,000. Once this system has been marketed for a few years and in-service accuracy and reliability have been demonstrated, it should be considered. For rigid pavement, the multi-wheel profilograph will probably remain the best alternative because its light weight allows testing before the pavement is fully cured. Also, traffic control during testing is not a factor because traffic is not allowed on the pavement until it is fully cured.

APPENDIX A

Theory and Listing of Program PROFIL

Program PROFIL

Program PROFIL takes road profile survey data and computes several smoothness statistics. It computes slope variance as measured by a chloe profilometer, inches per mile statistics as measured by the Rainhart Profilograph, and inches per mile statistics as measured by the reference quarter car simulator. Survey elevations must be taken every six inches along a roadway section not to exceed 1000 feet. Each reading should be recorded to the nearest one thousenth of a foot.

Data is inputted to PROFIL with sixteen readings on each card. Columns 1-14 of each card is for a alpha-numeric description of the test section. Columns15-16 is for a card sequence number. Cards must be numbered sequentially in order to be accepted by the program. Colums 17-20, 21-24, 25-28,....77-80 are for 16 elevations each recorded in thousenths of feet. Because only four columns are available, 9.999 feet is the maximum elevation that can be inputted.

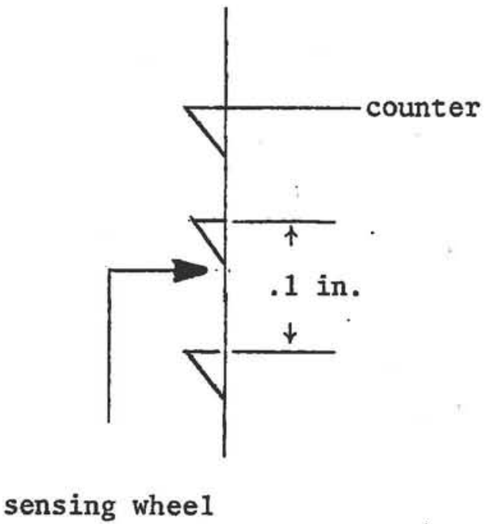
After the program inputs all the data checking for proper sequence of all the cards. The slope variance is computed. First, the absolute slope of the reference plane established by chloe is determined. This is accomplished by taking the difference between the sample elevation and the elevation 25 feet ahead of the sample position. This difference is then divided by 25 feet to get an absolute slope. Since CHLOE measures slope over a nine-inch spacing, special adjustments must be made to extract this from data spaced at a 6-inch spacing. Three survey points are used. Survey points I-1 and I-2 are averaged. The difference between survey point I and this average determines the slope over 9 inches. The magnitude of this slope is then tested to find errors in the data set. Any slope greater than .018 is flagged. First, the average slope as measured by chloe over the entire section is determined and then the variance equation is evaluated, as given below.

$$\sigma = \frac{\sum_{i}^{N} (Y_i - \bar{Y})^2}{N}$$

where σ is the slope variance, Y_i is the slope at point i as measured by chloe, $\bar{Y}$ is the average slope, and N is the number of survey points. σ is then divided by one million in order to adjust it to the conventional scale.

The in/mi statistics, as measured by the Rainhart Profilograph, is computed next. There is both a filtered and unfiltered statistic that needs to be computed. The first step is to determine the average elevation of the machine. This is accomplished by computing the average value of the 25 elevations before and 25 elevations after the sample point. This establishes an average elevation over 25 feet (6 in. between readings). This is not exactly what the profilograph measures, for it averages the elevation along 12 separate paths. Since the survey data is only available along one path, this is the best that can be done. The unfiltered statistics is determined by accumulating any negative change in the difference between the profilograph elevation and the sample point elevation.

Determining the filtered statistic requires detailed consideration of the behavior of the filter. The filter is basically a ratchet with 1/10 in. backlash. Below is a sketch.



The sensing wheel may have to move as much as 0.1 in. in the downward direction in order to move the counter. Depending on where the sensing wheel is positioned in the lash gap, the sensing wheel may move somewhat less than 0.1 in. before moving the counter. Because of ratchet effect, the counter will not respond to upward movement of elevations. After observing the behavior of the filter, it was discovered that the lash gap was actually 0.12 inches rather than 0.1 inch specified; therefore, .01 feet (.12 in.) was used in the program:

The final statistic generated was based on the response of a quarter car simulator. This required a numerical solution of a pair of differential equations given in NCHRP report 228 titled"Calibration of Response-Type Road Roughness Measuring Systems." The solution to these equations is presented in the appendix.

The response was based on a speed of 40 mi/hr which means .0085 sec between each survey point. The spring constants and damping coefficients were set to correspond to the reference quarter car simulator. They are as follows:

$K_s/M_s = 62.3 \text{ sec}^{-2}$

$K_t/M_s = 653 \text{ sec}^{-2}$

$M_u/M_s = .150$

$C_s/M_s = 6 \text{ sec}^{-1}$

where K_s = spring constant of vehicle suspension

M_s = mass of vehicle supported by spring

K_t = spring constant of tire

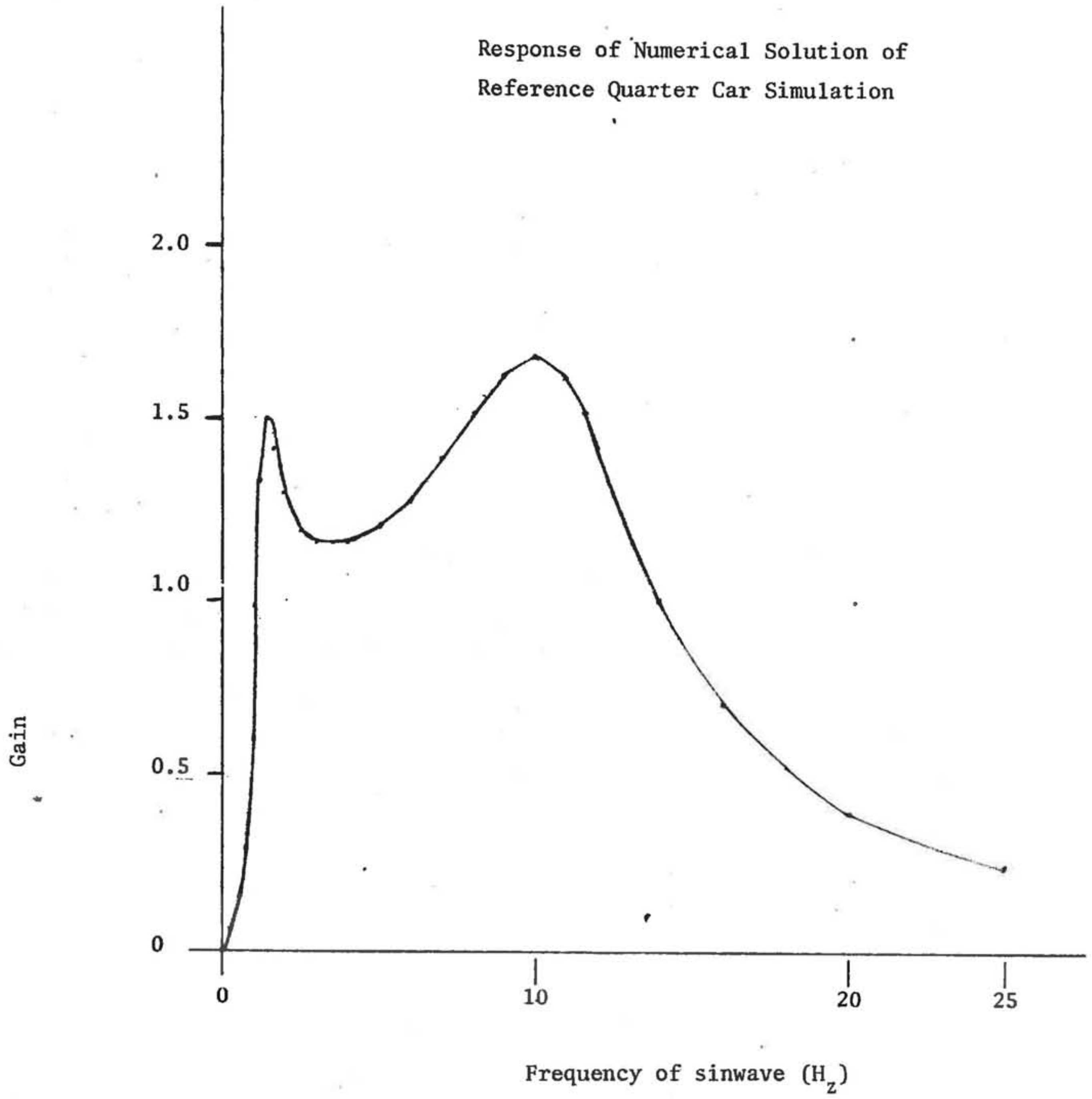
M_u = mass of wheel

C_s = damping coefficient of shock absorber

After the response of the vehicle is determined, any positive movement between the wheel and the vehicle is accumulated to obtain TRD (total rectified displacement). By dividing this by the length of the section and converting units, we get the inches per mile statistic. By multiplying by the speed, we get the average rectified velocity.

As a test, the program was driven with a sinewave and the attached response curve was generated. This curve compares well with the ideal response curve of the reference system in NCHRP report 228. The resulting slope variance results were also as expected.

1-26-82



Response of Numerical Solution of Reference Quarter Car Simulation

Numerical solution to the standard quarter car simulator differential equations

From page 43 of NCHRP 228

The equations of motion are as follows:

$$M_s \ddot{Z}_s + C_s(\dot{Z}_s - \dot{Z}_u) + K_s\ (Z_s - Z_u) = 0$$

$$M_s \ddot{Z}_s + M_u \ddot{Z}_u + K_t Z_u = K_t Z$$

let $Z_s\ (t+t_s) = Z_{s3}$ $\quad$ $Z_u\ (t+t_s) = Z_{u3}$ $\quad$ $Z_3 = Z\ (t+t_s)$

$Z_s\ (t) = Z_{s2}$ $\quad$ $Z_u\ (t) = Z_{u2}$ $\quad$ $Z_2 + Z\ (t)$

$Z_s\ (t-t_s) = Z_{s1}$ $\quad$ $Z_u\ (t-t_s) = Z_{u1}$ $\quad$ $Z_1 = Z\ (t-t_s)$

where t_s is the timestep

It follows for a small enough timestep that

$$\dot{Z}_s(t) \simeq \frac{Z_{s3} - Z_{s1}}{2t_s}, \quad \dot{Z}_u(t) \simeq \frac{Z_{u3} - Z_{u1}}{2t_s}$$

$$\ddot{Z}_s(t) \simeq \frac{Z_{s3} - 2Z_{s2} + Z_{s1}}{t_s^2}, \quad \ddot{Z}_u(t) \simeq \frac{Z_{u3} - 2Z_{u2} + Z_{u1}}{t_s^2}.$$

As a first approximation the differential equations at "t" can be written

$$1 \quad M_s \frac{(Z_{s3}-2Z_{s2}+Z_{s1})}{t_s^2} + C_s \frac{(Z_{s3}-Z_{s1}-Z_{u3}+Z_{u1})}{2t_s} + K_s\ (Z_{s2}-Z_{u2}) = 0$$

$$2 \quad M_s \frac{(Z_{s3}-2Z_{s2}+Z_{s1})}{t_s^2} + M_u \frac{(Z_{u3}-2Z_{u2}+Z_{u1})}{t_s^2} + K_t Z_{u2} = K_t Z_2$$

These equations can be rearranged:

$$\left(\frac{1}{t_s^2} + \frac{C_s}{2M_s t_s}\right) Z_{s3} + \left(\frac{-C_s}{2M_s t_s}\right) Z_{u3} = \frac{2Z_{s2}-Z_{s1}}{t_s^2} + \frac{C_s}{M_s}\left(\frac{Z_{si}-Z_{ui}}{2t_s}\right) + \frac{K_s}{M_s}(Z_{u2}-Z_{s2})$$

$$\left(\frac{1}{t_s^2}\right)Z_{s3} + \left(\frac{M_u}{M_s}\frac{1}{t_s^2}\right) Z_{u3} = \frac{2Z_{s2}-Z_{s1}}{t_s^2} + \frac{M_u}{M_s}\left(\frac{2Z_{u2}-Z_{u1}}{t_s^2}\right) + \frac{K_t}{M_s}(Z_2-Z_{u2})$$

If we let the coefficients of Z_{s3} and Z_{u3} be A_1 and B_1 for the first equation and A_2 and B_2 for the second equation and C_1 and C_2 be the right side of the two equations.

$$A_1Z_{s3} + B_1Z_{u3} = C_1$$

$$A_2Z_{s3} + B_2Z_{u3} = C_2$$

therefore

$$Z_{s3} = \frac{\begin{vmatrix} C_1 & B_1 \\ C_2 & B_2 \end{vmatrix}}{\begin{vmatrix} A_1 & B_1 \\ A_2 & B_2 \end{vmatrix}} \qquad Z_{u3} = \frac{\begin{vmatrix} A_1 & C_1 \\ A_2 & C_2 \end{vmatrix}}{\begin{vmatrix} A_1 & B_1 \\ A_2 & B_2 \end{vmatrix}}$$

As a second approximation, we can take the first approx. of Z_{s3} and Z_{u3} and revise the value of Z_{s2} and Z_{u2}. Equation 1 and 2 can be rearranged as follows:

$$\left(\frac{-2}{t_s^2} + \frac{K_s}{M_s}\right) Z_{s2} + \left(\frac{-K_s}{M_s}\right) Z_{u2} = -\left(\frac{Z_{s3}+Z_{s1}}{t_s^2}\right) + \frac{C_s}{M_s}\left(\frac{Z_{s1}-Z_{s3}-Z_{u1}+Z_{u3}}{2t_s}\right)$$

$$\left(\frac{-2}{t_s^2}\right) Z_{s2} + \left(\frac{K_t}{M_s} - \frac{M_{u2}}{M_s t_s^2}\right) Z_{u2} = \frac{K_t Z_2}{M_s} - \left(\frac{Z_{s3}+Z_{s1}}{t_s^2}\right) - \frac{M_u}{M_s}\left(\frac{Z_{u3}+Z_{u1}}{t_s^2}\right)$$

Defining the coefficients of Z_{s2} and Z_{u2} as D_1, E_1, D_2, and E_2. Defining the constants as F_1 and F_2. The equations become

$$D_1 Z_{s2} + E_1 Z_{u2} = F_1$$

$$D_2 Z_{s2} + E_2 Z_{u2} = F_2$$

therefore

$$Z_{s2} = \frac{\begin{vmatrix} F_1 & E_1 \\ F_2 & E_2 \end{vmatrix}}{\begin{vmatrix} D_1 & E_1 \\ D_2 & E_2 \end{vmatrix}} \qquad Z_{u2} = \frac{\begin{vmatrix} D_1 & F_1 \\ D_2 & F_2 \end{vmatrix}}{\begin{vmatrix} D_1 & E_1 \\ D_2 & E_2 \end{vmatrix}}$$

Description of Variables in Program PROFIL2

Variable	Description
ARV	Average Rectified Velocity in in./sec.
AV25	Average elevation over 25 feet in feet
CHSLP	Slope of CHLOE reference plane
DELTA	Change in elevation between two adjacent readings in feet
DESC1	Two word array of description of survey data
DESC2	same as above except for next card
EL (I)	Elevation of the Ith point on the roadway in feet (each point is 6 inches apart)
HNEW	Present elevation with respect to profilograph reference frame in feet
HOLD	Previous elevation with respect to profilograph reference frame in feet
I	do loop index
IE	Index of last elevation on current data card
IPM	Inches per mile statistic based on quarter car simulator
IS	Index of first elevation on current card
ISS	Truncated value of position of ratchet pointer on the profilograph filter
J	Do loop index.
LENGTH	length of test section in miles
N	number of elevation points in data set

NCARD	sequence number coded on input card
NCOUNT	count of number of data card inputted
S	position of pointer of ratchet on the profilograph filter
SUM	Total rectified vertical movement of sensing wheel on profilograph in feet
SUMF	Total of filtered vertical movement of sensing wheel on profilograph in feet (later in inches/mile)
TRD	Total rectified displacement between axle and frame of quarter car simulator in feet
VAR	Slope variance as would be measured by chloe
Y	Slope of the roadway
YBAR	Average slope as measured by CHLOE

Description of Variables in

Subroutine Q C^s

Variable	Description
A 1	coefficient of ZS3 in the first equation in sec^{-2}
A 2	coefficient of ZS3 in the second equation in sec^{-2}
B 1	coefficient of Zu3 in the first equation in sec^{-2}
B 2	coefficient of Zu3 in the second equation in sec^{-2}
CSMS	ratio of shock damping constant to mass of vehicle in sec^{-1}
C 1	constant term for first equation in sec^{-2}
C 2	constant term for second equation in sec^{-2}
DET	determinate of the coefficients for Zs2—Zu2 equations
DET2	determinate of the coefficients for Zs2—Zu2 equations
DIS	displacement during current timestep in feet
D 1	coefficient of Zs2 in the first equation in sec^{-2}
D 2	coefficient of Zs2 in the second equation in sec^{-2}
E 1	coefficient of Zu2 in the first equation in sec^{-2}
E 2	coefficient of Zu2 in the second equation in sec^{-2}
F 1	constant term of first equation of Zs2 and Zu2
F 2	constant term of second equation of Zs2 and Zu2
KSMS	ratio of suspension system spring constant to vehicle mass in sec^{-2}
MUMS	ratio of mass of wheel and axle to mass of vehicle
TRD	total rectified displacement in feet
TS	time step in sec
TSSQ	square of timestep in sec^2
ZS1	relative vertical position of vehicle one timestep before current time in feet
ZS2	relative vertical position of vehicle at current time in feet
ZS3	relative vertical position of vehicle at one timestep after current time in feet

Variables	Description
Zu 1	relative vertical position of axle one timestep before current time in feet
Zu 2	relative vertical position of axle at current time in feet
Zu 3	relative vertical position of axle one timestep after current time in feet
Z2	vertical elevation of the roadway where the tire is at the current time in feet
Z3	vertical elevation of the roadway where the tire is at one timestep after the current timestep in feet

```
      PROGRAM PROFIL(INPUT,OUTPUT)
C   THIS PROGRAM READS IN SURVEY DATA AND COMPUTES
C   SLOPE VARIANCE, AND INCHES PER MILE STATISTIC.
      REALYY(2016)
      REAL EL(2016),DESC1(2),DESC2(2),LENGTH,IPM
      READ 1,DESC1,NCARD,(EL(I),I=1,16)
    1 FORMAT(A10,A4,I2,16F4.3)
 2    NCOUNT = 1
 3    IS=NCOUNT*16+1
      IE=(NCOUNT+1)*16
      NCOUNT=NCOUNT+1
      READ1,DESC2,NCARD,(EL(I),I=IS,IE)
      IF(DESC2(1).NE.DESC1(1))GO TO 5
      IF(DESC2(2).NE.DESC1(2))GO TO 5
      IF(NCOUNT.EQ.NCARD)GO TO 3
      PRINT 4,DESC2,NCARD,NCOUNT
 4    FORMAT(1X,A10,A4,I2,* CARD OUT OF SORT AT COUNT*
     2 * OF *I2* --FATAL--*)
      STOP
 5    N=IE-16
      HOLD=0.0
      S=0.005
C ADJUST N FOR INCOMPLETE LINE
      DO6I=N-15,N
 6    IF(EL(I).LE.0.0)GO TO 7
      GO TO 8
  7   N=I-1
C    COMPUTING VARIANCE
 8    VAR=0.0
      YBAR=0.0
      DO15I=3,N
      IF(I.GT.N-51)GO TO 15
      CHSLP=(EL(I+51)-EL(I))/25.
 15   YBAR=YBAR+(EL(I)-(EL(I-1)+EL(I-2))/2.)*4./3.-CHSLP
      YBAR=YBAR/N
      DO 9 I=3,N
C   COMPUTING SLOPE OVER 9 IN. WHEEL SPACING
      Y=(EL(I)-(EL(I-1)+EL(I-2))/2.)*4./3.
      IF(Y.GT..018)PRINT33,I,EL(I-1),EL(I)
 33   FORMAT(* EXTREME VARIATION AT *I5,*TH ENTRY--*2F6.3)
      IF(I.GT.N-51) GO TO 9
      CHSLP=(EL(I+51)-EL(I))/25.
  9   VAR=VAR+(Y-YBAR-CHSLP)**2
C   NORMALIZNG SLOPE AND MULTIPLYING BY 1 MILLION PER CONVENTION
      VAR=VAR*1.0E+06/(N-2)
C   COMPUTING IN/MI STATISTIC
      SUM=0.0
      SUMF=0.0
      DO 12 J=25,N-25
      AV25=0.0
C     COMPUTING AVERAGE OVER 25 FT.
```

```
      DO 11 I=J-24,J+25
 11   AV25=AV25+EL(I)
      AV25=AV25/50.
      HNEW=EL(J)-AV25
      IF(J.LE.25)GO TO 12
      DELTA=HOLD-HNEW
      IF(S.GT.DELTA)GO TO 10
      SUMF=SUMF+DELTA-S
      S=0.0
      GO TO 14
 10   S=S-DELTA
      ISS=S/.01
      S=S-ISS*.01
 14   IF(DELTA.LT.0.0)DELTA=0.0
      SUM=SUM+DELTA
 12   HOLD=HNEW
C  COMPUTING LENGTH
      LENGTH=(N-50)*.5/5280.
C  SCALING TO IN./MI.
      SUM=12.*SUM/LENGTH
      SUMF=12.*SUMF/LENGTH
C  COMPUTING STATISTICS THAT WOULD BE GENERATED
C  FROM A RTRRM AT 40 MI/HR.
      TRD=0.0
      CALL QCS(TRD,EL(1))
      CALL QCS2(TRD,EL(2))
      DO 13 I=3,N
 13   CALL QCS1(TRD,EL(I))
C  COMPUTING IN/MI STATISTIC
      IPM=TRD*12.*10560./(N-1)
C  COMPUTING AVERAGE RECTIFIED VELOCITY IN IN/SEC
      ARV=TRD*40.*12.*10560./((N-1)*3600.)
C PRINTING RESULTS
      PRINT 31,DESC1,YBAR,VAR,SUM,SUMF,IPM,ARV
 31   FORMAT(1X,A10,A4,* AVERAGE SLOPE = *F10.5*, SLOPE VARIANCE= *
     2 F10.5,/*, RAW STATISTIC *F10.5*, FILTERED STATISTIC *F10.5
     3* IN./MI.*/,1X,* RTRRM STATISTICS ARE *F10.5* IN/MI AND *F10.5
     4* IN/SEC.*)
      IF(DESC2(1).EQ.1H  )STOP
      DESC1(1)=DESC2(1)
      DESC1(2)=DESC2(2)
      DO 32 I=1,16
      EL(I)=EL(IS)
 32   IS=IS+1
      GO TO 2
      END
      SUBROUTINE QCS(TRD,Z3)
C  THIS ROUTINE DETERMINES THE RECTIFIED DISPLACEMENT
C  BETWEEN  THE AXLE AND CAR BASED ON THE DIFERENTIAL
C  EQUATIONS FOR THE STANDARD QUARTER CAR SIMULATOR.
C  PAGE 43 NCHRP NO. 228
      REAL KSMS,KTMS,MUMS,IN
```

```
      DATA TS,KSMS,KTMS,MUMS,CSMS/.0085,62.3,653.,.150,6./
C   INTIALIZING
      ZU1=ZU2=ZU3=ZS1=ZS2=ZS3=Z2=Z3
C   COMPUTING CONSTANTS
      TSSQ=TS**2
      A1=1./TSSQ + CSMS/(TS*2.)
      B1=-CSMS/(TS*2.)
      A2=1./TSSQ
      B2=MUMS/TSSQ
      DET=A1*B2-B1*A2
      D1=KSMS-2./TSSQ
      E1=-KSMS
      D2=-2./TSSQ
      E2=KTMS-2.*MUMS/TSSQ
      DET2=D1*E2-D2*E1
      RETURN
      ENTRY QCS1
C   REFINING VALUE FOR ZU2 AND ZS3
      F1=CSMS*(ZS1-ZS3-ZU1+ZU3)/(2.*TS)-(ZS1+ZS3)/TSSQ
      F2=KTMS*Z2-(ZS1+ZS3)/TSSQ-MUMS*(ZU1+ZU3)/TSSQ
      ZU2=(D1*F2-D2*F1)/DET2
      ZS2=(F1*E2-F2*E1)/DET2
C   COMPUTING TOTAL RECTIFIED DISPLACEMENT
      DIS=ZS2-ZS1-ZU2+ZU1
      IF(DIS.LT.0.0)DIS=0.0
      TRD=TRD+DIS
      Z2=Z3
      ZU1=ZU2
      ZU2=ZU3
      ZS1=ZS2
      ZS2=ZS3
      ENTRY QCS2
C   FINITE DIFFERENCE SOLUTION FIRST APPROX FOR ZU3 AND ZS3
      C1=(2*ZS2-ZS1)/TSSQ+(ZS1-ZU1)*CSMS/(TS*2.)+KSMS*(ZU2-ZS2)
      C2=(2*ZS2-ZS1)/TSSQ+(2*ZU2-ZU1)*MUMS/TSSQ+KTMS*(Z2-ZU2)
      ZU3=(A1*C2-A2*C1)/DET
      ZS3=(C1*B2-C2*B1)/DET
      RETURN
      END
```

```
      PROGRAM PERFECT(INPUT,OUTPUT,TAPE1)
      DIMENSION IVAR(16)
C  THIS PROGRAM CREATES SURVEY DATA BASED ON A PERFECTLY FLAT
C  ROADWAY.  THE ONLY VARIATION IN THE DATA IS THE RANDOM ERROR
C  EXPECTED IN THE DATA.  MONTE CARLO SIMULATION OF A PERFECT
C  ROADWAY.
      REWIND 1
      PRINT 10
 10   FORMAT(* ENTER SEED FOR RANDOM NUMBER GENERATOR*)
      PRINT 11
 11   FORMAT(* AND STANDARD DEVIATION OF DATA (SIGMA)*)
      READ,SEED, SIGMA
      CALL RANSET(SEED)
      DX = .1
      DO 9 N=1,66
      DO 7 J=1,16
      R=RANF(1)
      IF(R.LT..0002)GO TO 1
      IF(R.GT..9998)GO TO 4
      P=.0002
      X2=-3.5
      DO 2 I=1,100
      X1=X2
      X2=X2+DX
      P1=.19947114*DX*(EXP(-X1**2/2.)+EXP(-X2**2/2.))
      P=P+P1
      IF(P.GT.R) GO TO 3
 2    CONTINUE
      STOP 99
 3    X=X2-(P-R)*(X2-X1)/P1
      GO TO 6
 1    X= -3.5
      GO TO 6
 4    X=3.5
 6    CONTINUE
 7    IVAR(J)=X*SIGMA + 4.*SIGMA + .5
 9    WRITE(1,8) N,IVAR
 8    FORMAT(* PERFECT ROAD *,I2,16I4)
      REWIND 1
      STOP
      END
```

APPENDIX B

Monte Carlo Simulation of Errors in the Survey Data

As with any measurement, there is a certain amount of error inherent in the survey data. The error is expected to be random and normally distributed. The characteristic width (o) of the distribution was estimated to be 0.002 feet, i.e., the standard error of the survey reading is expected to be 0.002 feet. Based on the shape of a normal distribution curve, 68% of the readings will fall within ±0.0002 feet of the true value.

This error in taking survey elevations will reveal itself as noise in the simulation. In order to determine the effect of this noise on the simulated statistic, a data set was created by Program PERFECT (listing attached), representing a perfectly flat road. Random variation in the elevation date within the expected error range of the readings was included. This data was then used by Program PORFIL, the roughness meter simulation program, to compute various roughness statistics.

Ideally, the roughness statistics generated by a perfectly flat roadway should be zero. However, the random error introduced while 'measuring' this perfectly flat road will result in non-zero statistics. In fact, the roughness indication due to the measurement noise is substantial. The results are incicated below:

CHLOE slow variance - 12
Unfiltered profilograph in./mi. - 142
Filtered profilograph in./mi. - 18
RTRRM in./mi. - 40

This noise is expected to be fairly constant regardless of the roughness of the road being surveyed. That is, the magnitude of the error of the survey data will be the same wheter the roadway is rough or smooth. This will result in simple offsets of all the statistics generated with the survey data. Incorporating these offsets into the simulated statistics brings them in line with the expected results.

The most important correlation for this study is the filtered profilograph statistic as simulated with the survey data versus the actual measured filtered statistic (see Figure 7). The best fit straight line through this data is close to unity (1.05) and has an intercept which is near that expected from the survey error noise (20). It should be noted that the expected offset due to measurement noise is only a rough estimate because the error magnitude is only a rough estimate.

Similarly, a best linear fit of the RTRRM simulated statistic versus the measured filtered statistic results in an intercept close to what is expected due to error noise (see Figure 9). For the CHLOE simulation versus the measured filtered statistics, a second order curve fit will result in an intercept which corresponds to the expected noise offset (see Figure 8). A second order curve is used here because of the nature of the CHLOE statistic.

Similar results can be obtained upon curve fitting the RTRRM and CHLOE statistic versus the unfiltered profilograph measurements (see Figures 5 and 6). In this case, the lower right hand point was discounted as bad data probably due to excessive speed during the profilograph run.

For the case of the unfiltered statistic simulation versus the actual measurements, results are not very good. The zero intercept is about one-half of the Monte Carlo simulated noise levels listed above. The reason for this is probably due to the nature of the error in the survey data. The surveryor will tend to read the same elevation until there is a discernable change in the elevation. This will tend to make the simulated unfiltered statistic due to error smaller than if the errors were completely random. The other statistics are not sensitive to this difference because of the filtering.

(The CHLOE statistic inherently is not affected).

The noise generated by the Monte Carlo simulation is white noise and it spans over a broad spectrum of wave lengths, while the actual error contains little shortwave component (1 foot). This is because of the surveyor's tendency to read the same elevation on successive readings. Below are two graphs depicting this phenomena.

 σ = .9 unfiltered statistic = 3

 σ = .9 unfiltered statistic = 2

Both curves have the same average and standard deviation (σ) while the shorter wave length curve has a higher inches per mile statistic.

APPENDIX C

Proposed AASHTO Specifications for Roadway Smoothness

Optional Addition: Surface Test Inspection. The smoothness of the pavement will be determined by using a profilograph over each designated lane. The surface finish of mainline pavement where the posted speed will be 40 miles per hour (MPH) or higher shall be tested and corrected to a smoothness as herein described except pavement surfaces that are specifically excluded by contract documents.

Pavement mainline is defined as all pavement for traffic lanes and climbing lanes, but excluding acceleration and deceleration lanes and all tapered sections, pavement widening, shoulders, and side street returns. Pavement on horizontal curves having a centerline radius of curveature less than 1000 feet and pavement within the super elevation transition of such curves will also be excluded. These pavements will be tested by a 10-foot straightedge.

Equipment: The Profile Index will be determined utilizing a profilograph in accordance with California Test Method 526 suggested. The equipment furnished and operated by the Department shall consist of a frame at least 20 feet in length supported upon multiple wheels having no common axle. The wheels are arranged in a staggered pattern such that no two wheels cross the same bump at the same time. The profile is recorded from the vertical movement of a sensing wheel attached to the frame at midpoint and is in reference to the mean elevation of the twelve points of contact with the road surface established by the support wheels. The profilogram is recorded on a scale of 1 inch, or full scale, vertically. The sensing or profile wheel shall consist of a bicycle-type wheel with a 5-foot circumference. Motive power may be provided manually or by the use of a propulsion unit attached to the center assembly. In operation, the profilograph shall be moved longidudinally along the pavement at a speed no greater than 3 MPH so as to eliminate as much bounce as possible.

Surface Test: The contractor shall furnish paving equipment and employ methods that produce a riding surface having a Profile of (12) inches per mile, or less. The profile will terminate 50 feet from each bridge approach pavement or existing pavement which is jointed by the new pavement.

Pavement profiles will be taken 3 feet from and parallel to each edge of pavement for pavement placed at a 12-foot width or less. When pavement is placed at a greater width than 12 feet, the profile will be taken 3 feet from and parallel to each edge and at the approximate location of each planned longitudinal joint. Additional profiles may be taken only to define the limits of an out of tolerance surface variation.

During the initial paving operations, either when starting up or after a long shut down period, the pavement surface will be tested with the profilograph as soon as the concrete has cured sufficiently to allow testing. Membrane curing damaged during the testing operation shall be repaired by the contractor as directed by the Engineer. The purpose of this initial testing is to aid the contractor and the Engineer in evaluating the paving methods and equipment. Once the initial pavement smoothness, paving methods and paving equipment are acceptable to the Engineer, the contractor may proceed with the paving operation. Subsequent to the aforementioned initial testing, daily profiles of each day's paving will be run as soon as possible, preferably during the next working day following placement of the pavement.

A daily average Profile Index will be determined for each day's paving. A day's paving is defined as a minimum of 1000 linear feet of full-width pavement placed in a single day. If less than 1000 linear feet is paved, the day's production shall be grouped with the subsequent day's production. If an average Profile Index of (15) inches per mile is exceeded in any daily paving operation, the paving operation will be suspended and will not be allowed to resume until corrective action is taken by the contractor. In the event that paving operations are suspended as a result of the average Profile Index exceeding (15) inches per mile, subsequent paving operations will be tested in accordance with the initial paving testing procedures.

All areas represented by high points having deviations in excess of (0.3) inches in 25 feet or less shall be removed by the contractor with an approved grinding device or a device consisting of multiple diamond saw blades. The use of a bush hammer or other impact devices will not be permitted. Deviations in excess of (0.3) inches will be determined from the profilogram in accordance with Department Test Methods.

On those pavement sections where corrections are necessary, second profilograph runs will be performed to verify that corrections have produced an average Profile Index of (15) inches per mile or less. If the initial average Profile Index is less than (12) inches per mile, only the areas representing (0.3) inch deviations will be reprofiled for correction verification. All corrective work shall be completed prior to determinations of pavement thickness.

<u>Pay Adjustments</u>: For the purposes of pay adjustment, a section is defined as a minimum of 1000 feet or a day's paving. When the average Profile Index is less and (10) inches per section, an incentive payment will be made for the completed pavement. When the average Profile Index exceeds (10) inches per section but does not exceed (12) inches per section, payment will be made at the contract unit price for the completed pavement. When the average Profile Index exceeds (12) inches per section but does not exceed (15) inches per section, the contractor may elect to accept a contract unit price adjustment in lieu of reducing the average Profile Index. Contract unit price adjustments will be made in accordance with the following schedule in those cases when the contractor elects to accept contract unit price adjustments in lieu of reducing the average Profile Index. Price adjustment for a pavement which has been ground to reduce the Profile Index will be in accordance with the following schedule.

AVERAGE PROFILE INDEX	CONTRACT UNIT PRICE ADJUSTMENT*
Inches per mile per 0.1 mile section	Percent of pavement unit bid price
Less than (10) to (10) ? 10½m	108 or 105
over (10) to (12)	100 or 100
over (12) to (13)	98 or 98
over (13) to (14)	96 or 97
over (14) to (15)	92 or 95
over (15)	Corrective work required

This unit bid price adjustment will apply to the total area of the section for the lane width represented by the profile (usually 12 feet wide).

No payment will be made for any pavement which has an average Profile Index in excess of (15) inches per mile until corrective work has been completed by the contractor and the pavement reprofiled to verify that the average Profile Index has been reduced to (15) inches per mile or less.

*(ACPA believes either schedule is acceptable.)

APPENDIX D

California Test Method
526

STATE OF CALIFORNIA—BUSINESS AND TRANSPORTATION AGENCY

DEPARTMENT OF TRANSPORTATION
DIVISION OF CONSTRUCTION
Office of Transportation Laboratory
P. O. Box 19128
Sacramento, California 95819
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California Test 526
1978

OPERATION OF CALIFORNIA PROFILOGRAPH AND EVALUATION OF PROFILES

A. SCOPE

The operation of the California Profilograph, the procedure used for determining the Profile Index from profilograms of pavements made with the Profilograph, and the procedure used to locate individual high points in excess of 0.3 inch are described in Parts I, II and III, respectively, in this test method.

PART I. OPERATION OF THE CALIFORNIA PROFILOGRAPH

A. EQUIPMENT

The California Profilograph consists of a frame twenty-five feet in length supported upon wheels at either end. The profile is recorded from the vertical movement of a wheel attached to the frame at midpoint and is in reference to the mean elevation of the points of contact with the road surface established by the support wheels (see Figure 3). The profilogram is recorded on a scale of one inch equal to twenty-five feet longitudinally and one inch equal to one inch, or full scale, vertically. Motive power may be provided manually or by the use of a propulsion unit powered with a gasoline engine attached to the center assembly.

B. OPERATION

The instructions for assembling the Profilograph are contained in a booklet accompanying each unit. Particular attention should be paid to the listed precautions.

In operation, the Profilograph should be moved at a speed no greater than a walk so as to eliminate as much bounce as possible. Too high a speed will result in a profilogram that is difficult to evaluate.

Calibration of the Profilograph should be checked periodically. The horizontal scale can be checked by running a known distance and scaling the result on the profilogram. If the scale is off, the profile wheel should be changed to one of a proper diameter. The vertical scale is checked by putting a board of known thickness under the profile wheel and again scaling the result on the profilogram. If the scale is off, the cause of the incorrect height should be determined and corrected.

PART II. DETERMINATION OF THE PROFILE INDEX

A. EQUIPMENT

To determine the Profile Index, use a plastic scale 1.70 inches wide and 21.12 inches long representing a pavement length of 528 feet or one-tenth of a mile at a scale of 1" = 25'. A plastic scale for the profilograph may be obtained by the Districts from the Office of Business Management. Near the center of the scale is an opaque band 0.2 inch wide extending the entire length of 21.12 inches. On either side of this band are scribed lines 0.1 inch apart, parallel to the opaque band. These lines serve as a convenient scale to measure deviations or excursions of the graph above or below the blanking band. These are called "scallops".

B. METHOD OF COUNTING

Place the plastic scale over the profile in such a way as to "blank out" as much of the profile as possible. When this is done, scallops above and below the blanking band usually will be approximately balanced. See Figure 1.

The profile trace will move from a generally horizontal position when going around superelevated curves making it impossible to blank out the central portion of the trace without shifting the scale. When such conditions occur the profile should be broken into short sections and the blanking band repositioned on each section while counting as shown in the upper part of Figure 2.

Starting at the right end of the scale, measure and total the height of all the scallops appearing both above and below the blanking band, measuring each scallop to the nearest 0.05 inch (half a tenth). Write this total on the profile sheet near the left end of the scale together with a small mark to align the scale when moving to the next section. Short portions of the profile line may be visible outside the blanking band but unless they project 0.03 inch or more and extend longitudinally for two feet (0.08" on the profilogram) or more, they are not included in the count. (See Figure 1 for illustration of these special conditions).

When scallops occurring in the first 0.1 mile are totaled, slide the scale to the left, aligning the right end of the scale with the small mark previously made, and proceed with the counting in the same manner. The last section counted may or may not be an even 0.1 mile. If not, its length should be scaled to determine its length in miles. An example follows:

Section length, miles	*Counts, tenth of an inch*
0.10	5.0
0.10	4.0
0.10	3.5
400′ = 0.076	2.0
Total 0.376	14.5

The Profile Index is determined as "inches per mile in excess of the 0.2-inch blanking band" but is simply called the Profile Index. The procedure for converting counts of Profile Index is as follows:

Using the figures from the above example:

Length = 0.376 mile, total count = 14.5 tenths of an inch

Profile Index = (1 mile/length of profiles in miles) × total count in inches

PrI = (1/0.376) × 1.45 = 3.9

(Note that the formula uses the count in inches rather than tenths of an inch and is obtained by dividing the count by ten.)

The Profile Index is thus determined for the profile of any line called for in the specifications. Profile Indexes may be averaged for two or more profiles of the same section of road if the profiles are the same length.

Example:

	Section length, miles	*Counts, tenths of an inch* *Left wheel track*	*Right wheel track*
	0.10	5.0	4.5
	0.10	4.0	5.0
	0.10	3.5	3.0
400′ =	0.076	2.0	1.5
Total	0.376	14.5	14.0
PrI (by formula)		3.9	3.7

Averages = (3.9 + 3.7)/2 = 3.8

The specifications state which profiles to use when computing the average Profile Index for control of construction operations.

C. LIMITATIONS OF COUNT IN 0.1 MILE SECTIONS

When the specifications limit the amount of roughness in "any one-tenth mile section," the scale is moved along the profile and counts made at various locations to find those sections if any, that do not conform to specifications. The limits are then noted on the profile and can be later located on the pavement preparatory to grinding.

D. LIMITS OF COUNTS—JOINTS

When counting profiles, a day's paving is considered to include the last portion of the previous day's work, which includes the daily joint. The last 15 to 30 feet of a day's paving cannot usually be obtained until the following day. In general, the paving contractor is responsible for the smoothness of joints if he places the concrete pavement on both sides of the joint. On the other hand, the contractor is responsible only for the pavement placed by him if the work abuts a bridge or a pavement placed under another contract. Profilograph readings when approaching such joints should be taken in conformance with current specifications.

E. AVERAGE PROFILE INDEX FOR THE WHOLE JOB

When averaging Profile Indexes to obtain an average for the job, the average for each day must be "weighted" according to its length. This is most easily done by totaling the counts for the 0.1 mile sections of a given line or lines and using the total length of the line in the computation for determining the Profile Index.

PART III. DETERMINATION OF HIGH POINTS IN EXCESS OF 0.3 INCH

A. EQUIPMENT

Use a plastic template having a line one inch long scribed on one face with a small hole or scribed mark at either end, and a slot 0.3 inch from and parallel to the scribed line. See Figure 2. (The one inch line corresponds to a horizontal distance of 25 feet on the horizontal scale of the profilogram). The plastic template may be obtained from Office of Business Management.

B. LOCATING HIGH POINTS IN EXCESS OF 0.3 INCH

At each prominent peak or high point on the profile trace, place the template so that the small holes or scribe marks at each end of the scribed line intersect the profile trace to form a chord across the base of the peak or indicated bump. The line on the template need not be horizontal. With a sharp pencil draw a line using the narrow slot in the template as a guide. Any portion of the trace extending above this line will indicate the approximate length and height of the deviation in excess of 0.3 inch.

There may be instances where the distance between easily recognizable low points is less than one inch (25 feet). In such cases a shorter chord length shall be used in making the scribed line on the template tangent to the trace at the low points. It is the intent, however, of this requirement that the baseline for measuring the height of bumps will be as nearly 25 feet (1 inch) as possible, but in no case to exceed this value. When the distance between prominent low points is greater than 25 feet (1 inch) make the ends of the scribed line intersect the profile trace when the template is in a nearly horizontal position. A few examples of the procedure are shown in the lower portion of Figure 2.

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EXAMPLE SHOWING METHOD OF DERIVING PROFILE INDEX FROM PROFILOGRAMS

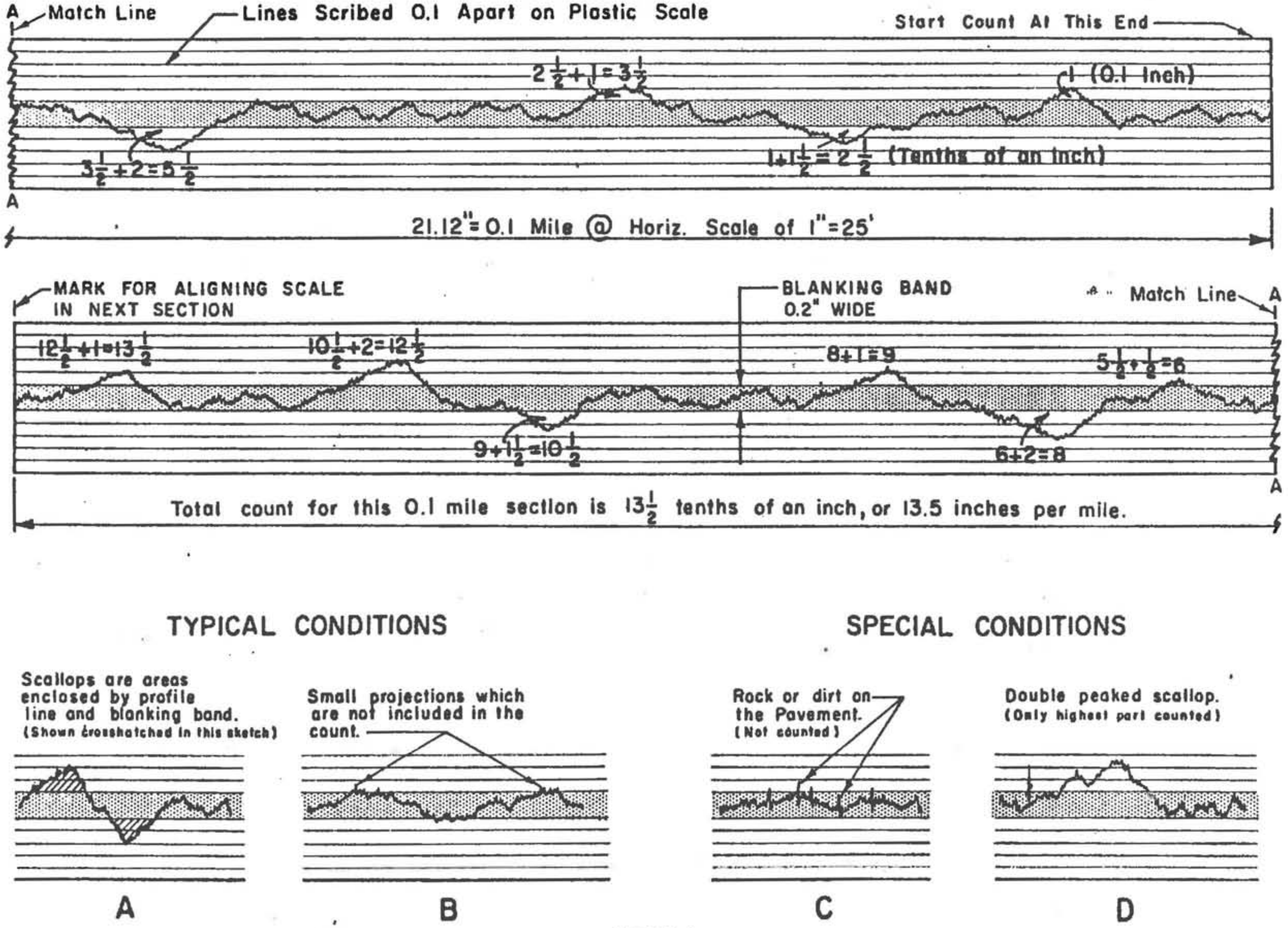
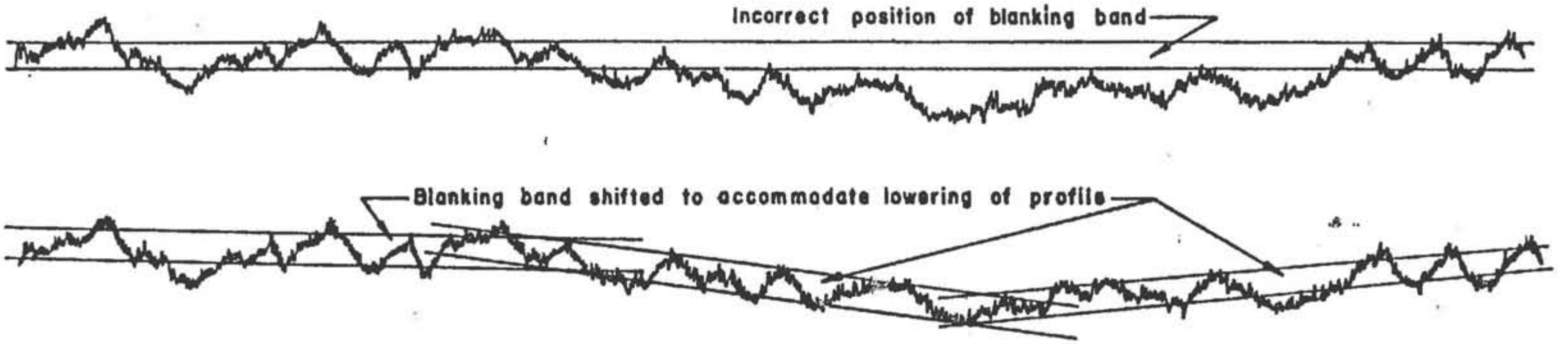
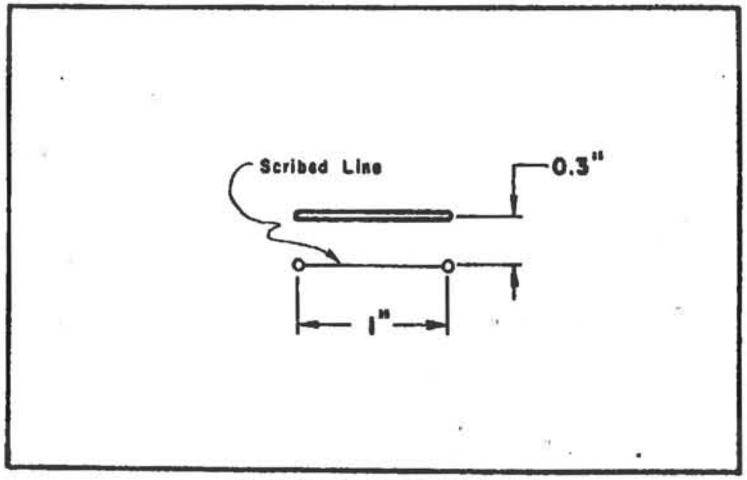


FIGURE I

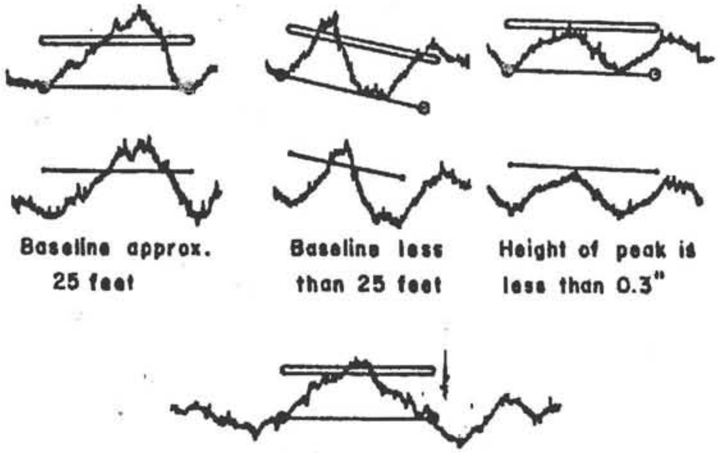
METHOD OF COUNTING WHEN POSITION OF PROFILE SHIFTS AS IT MAY WHEN ROUNDING SHORT RADIUS CURVES WITH SUPERELEVATION



METHOD OF PLACING TEMPLATE WHEN LOCATING BUMPS TO BE REDUCED



BUMP TEMPLATE



Baseline approx. 25 feet

Baseline less than 25 feet

Height of peak is less than 0.3"

Baseline more than 25'

FIGURE 2

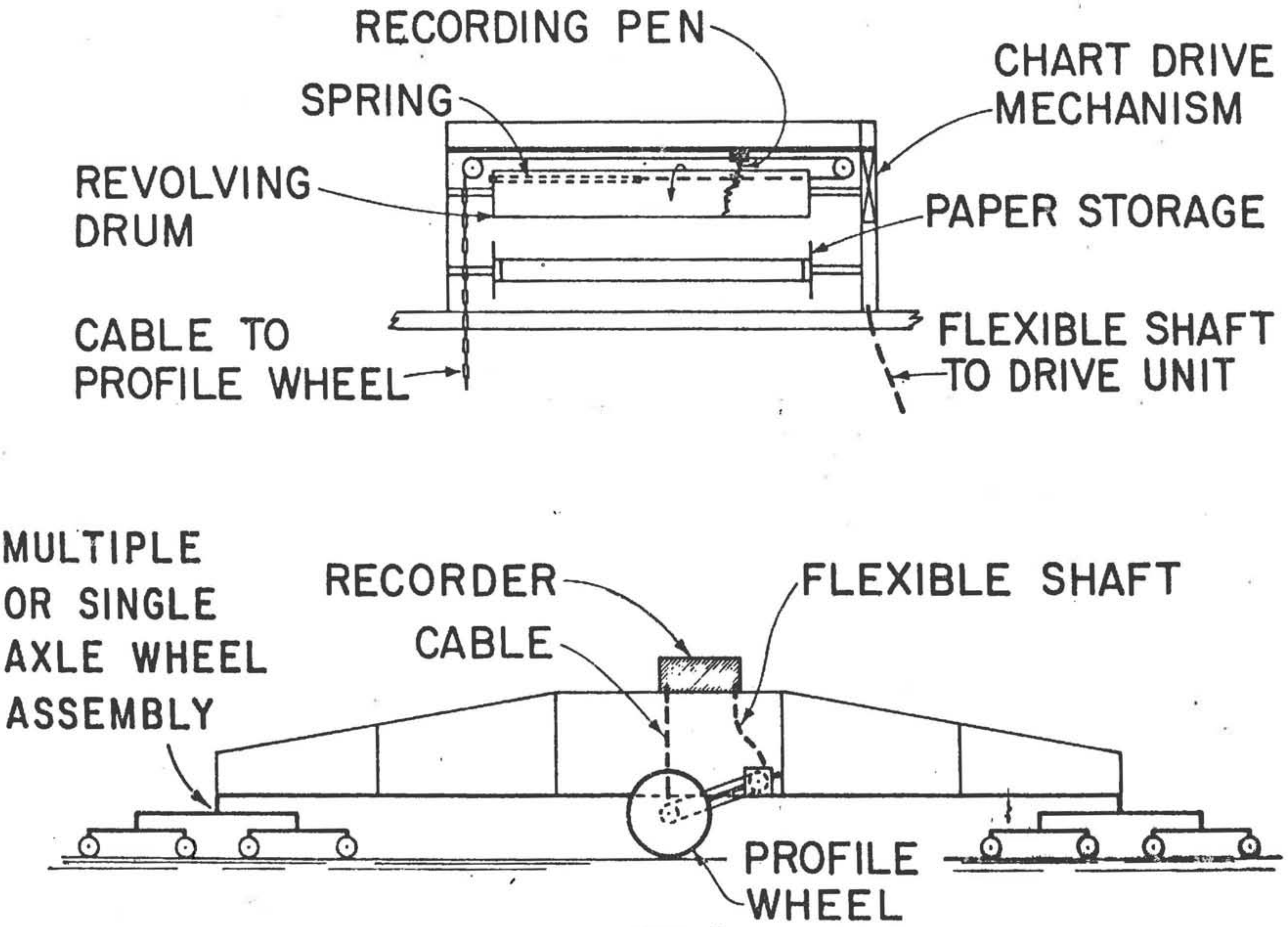

RECORDING PEN
SPRING
CHART DRIVE MECHANISM
REVOLVING DRUM
PAPER STORAGE
CABLE TO PROFILE WHEEL
FLEXIBLE SHAFT TO DRIVE UNIT
MULTIPLE OR SINGLE AXLE WHEEL ASSEMBLY
RECORDER
CABLE
FLEXIBLE SHAFT
PROFILE WHEEL

FIGURE 3