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16. Abstract

The construction of smooth and durable pavements is a major objective in construction projects. The Administration at TxDOT has asked that ride quality be stressed on all construction projects. TxDOT has focused on ride quality specifications and has revised them several times in the recent past. These specifications call for remedial action well after the concrete has hardened and it becomes necessary to grind the concrete, which leaves a permanent scar for the life of the pavement. If poor ride quality could be detected before the concrete reaches its initial set, a better product at less cost could potentially be achieved. The objective of this research is to determine if early detection of inadequate ride or smoothness in PCC pavements can be determined and if so, identify the appropriate correction procedures needed before the concrete has hardened.

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Improving Ride Quality of Portland Cement Concrete Pavement: Final Report

TECHNICAL REPORT 0-4385-1

PROJECT TITLE: Improving Ride Quality of Portland Cement Concrete Pavement
PROJECT NUMBER: 0-4385

THE UNIVERSITY OF TEXAS AT ARLINGTON
TRANSPORTATION INSTRUMENTATION LABORATORY

by

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Performed in Cooperation with the
Texas Department of Transportation
and the
Federal Highway Administration

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IMPLEMENTATION STATEMENT

During this project, a method was developed for early bump detection for use during pavement construction of Portland cement concrete pavements. While the existing specification stipulates that the cost for correcting deficiencies is to be borne by the contractor, in reality, penalties are factored into the contractor's bid. Thus, if a method for early bump detection is available for the contractor to use, the reduction in his or her risk could potentially translate to a lower bid with the result that a superior riding pavement is achieved at less cost.

DISCLAIMERS

The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the Texas Department of Transportation or the Federal Highway Administration. This report does not constitute a standard, specification, or regulation.

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ACKNOWLEDGEMENTS

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CHAPTER 1
INTRODUCTION

The objective of this research is to determine if early detection of inadequate ride or smoothness in Portland cement concrete (PCC) pavements can be determined and, if so, identify the appropriate correction device or procedures that can be applied before the concrete has hardened. TxDOT has placed an importance on developing or locating a device that can be used for the early detection of roughness in new PCC pavements. While the existing specification stipulates that the cost for correcting deficiencies is to be borne by the contractor, in reality, penalties are factored into the contractor's bid. Thus, if a method for early bump detection is available for the contractor to use, the reduction in his or her risk could potentially translate to a lower bid with the result that a superior riding pavement is achieved at less cost.

This research was conducted in accordance with TxDOT Project 0-4385, which was initiated for this effort. The primary objective of the project was to identify a suitable device for bump detection on newly poured concrete that would be consistent with the current ride specification. If a suitable device was not found, researchers would attempt to develop an early bump detection device in this project. During the course of work, two companies were working on devices that could possibly be used by contractors to detect bumps while the concrete is being placed. However, neither device was in production. It was decided to monitor the progress of the development of these two candidates and at the same time pursue the development of a suitable device. Details on this development are included in the report.

Background

In a recent National Quality Initiative (NQI) survey, pavement smoothness was identified as the most significant measure of pavement quality to the traveling public. The Texas Department of Transportation (TxDOT) has assigned a high priority to the construction of smooth pavements, introducing a smoothness specification based on measured surface profiles. In addition to providing a more accurate assessment of pavement smoothness, these specifications enable TxDOT to maintain a consistent historical record of a pavement's ride quality, providing pavement management with a "cradle to grave" smoothness statistic with which to monitor the highway network and ensure that roads are maintained at acceptable levels of smoothness.

In line with the philosophy of end-result specifications, TxDOT measures the surface smoothness of the as-built pavement for acceptance testing. The desired quality of work is specified in terms of the level of smoothness that must be achieved. The producer or contractor is allowed the fullest possible latitude in the methods through which the desired quality is met. If a method to check surface smoothness while paving is available, early detection of non-compliant areas would be possible, which may lead to more cost-effective alternatives for correcting deficiencies. This is particularly relevant to concrete pavement construction where the correction of bumps after the concrete has hardened becomes costly. In this instance, diamond grinding is typically done to improve the ride, but this treatment results in a permanent scar and in a reduction of the slab thickness specified in the plans.

Attempts at developing equipment for early bump detection (also referred to herein as a bump meter) were conducted in the early 1990s. Richard Deter, who worked for T.L Jones during this time period, developed a bump meter that consisted of a platform or bridge that would follow closely behind the paving machine. The bridge that straddled the concrete was approximately 25 feet in length in the direction of travel. Two beams or measurement bars along each wheel path were each instrumented with three acoustic sensors that measured the distance between the fresh concrete and the sensor. The instrument was designed to measure bumps in a manner somewhat similar to the profilograph and rolling straight edge. Iafrate Construction Company obtained the part of T.L. Jones that had this unit. Deter left the company not long after. In talking with one of the users of this device, however, there were a number of problems. One, the unit apparently had no way to easily record and mark the area that needed correcting. The unit would have to go back and forth over the area of the bump it appropriately identified. The unit was also self powered and often had problems with concrete or other obstacles along its wheels as it moved, thus providing an incorrect estimate of the bump. The process was hampered in that, by the time the bump was located, another area would have hardened. Finally, the unit was somewhat cumbersome to set up and operate.

Report Contents

This report first summarizes efforts in locating a suitable device for early detection of bumps on newly laid concrete pavements. The summary includes details about site visits to paving jobs to identify methods that could be applied for developing an early bump detection device. For example, researchers made a site visit to Ames Engineering, which had developed and was testing a possible device for this purpose. More detailed discussions of the site visits may be found in Appendix A.

Chapter 2 discusses the development efforts and testing of a ”pushcart,” which was initially developed at the University of Texas at Arlington on an earlier TxDOT project, for measuring bumps. The measuring concept used in this earlier work laid the foundation for the development of the "sliding profiler,"[1] a prototype device developed by project personnel for the early detection of bumps in newly laid concrete pavements. The sliding profiler development and testing is discussed in Chapter 3. Chapter 4 provides a summary of the project and recommendations for further testing and implementation. Appendix B provides details on tests conducted with a prototype device being developed by Ames Engineering for measurements of profile on wet concrete pavements.

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[1] Patent Pending

CHAPTER 2
THE UTA PUSHCART FOR BUMP MEASUREMENTS

Introduction

This chapter discusses the construction and testing of the pushcart developed at the University of Texas at Arlington (UTA) and how this work led to the development of the sliding profiler in this project. As noted in Chapter 1, during the first year of the project, existing practices for building smooth concrete pavements were investigated, site visits to various ongoing construction projects were made, and current instruments or procedures for early bump detection were investigated. This investigation is discussed in Appendix A.

Two companies were working on possible units that might be applicable for this purpose. Gomaco was developing a unit that appeared to be something similar to the original Deter bump meter but was not yet available. Ames Engineering was testing a device called the Real Time Profiler (RTP). The Ames unit used three lasers that were moved along the pavement and used to measure the pavement profile. The version viewed at the site visit to Ames Engineering was pushed along the pavement (see Figure 2.1). The use of the RTP for measuring profile and bumps was later tested at the Texas A&M Riverside Campus (see Appendix B). Ames has also attached the RTP to a paver on tests conducted by the company on concrete paving projects. At that time, neither the Ames or the Gomaco units were available, although Ames Engineering appeared closest to having a working system with its prototype RTP. In view of this finding, it was decided at a project meeting to investigate a modified version of the UTA low-speed pushcart profiler, which was developed during an early research project at UTA in the late 1980s.

The UTA Pushcart

The idea behind investigating the old UTA pushcart concept for measuring bumps on newly poured concrete was based on observations of the autofloat unit during one of the site visits in Phase I of the research project. In this visit, researchers came up with the idea of a floating or sliding profiler while watching the autofloat as it slid side to side along the pavement.

Since the pushcart determines an estimate of profile by summing the vertical displacements as the device is pushed along the pavement, researchers thought that the method would possibly work in a similar manner. Instead of the measuring platform rolling along the pavement, it could ”slide”' along the wet concrete.

Figure 2.1. Ames Engineering RTP.

The pushcart, however, was no longer being used and had been kept outside one of the TxDOT shop areas in Austin. Because it was left out in the open, a number of the parts had rusted. It was returned to UTA and attempts were made to refurbish it, replacing the distance encoder and several of the rusted parts. The basic measuring concept of the UTA unit was a solid state gyroscope placed on a 12-inch measurement platform, which was free to move vertically as it was pushed on a pavement or other such structure. As the pushcart moved longitudinally along the pavement, the gyroscope measured the slope or displacement angles of the floating measurement base, as illustrated in Figure 2.2. An estimate of the profile was then computed by the sum of products of the length of the measurement platform and its angle with respect to the horizon at the different measurement locations along the test wheel path.

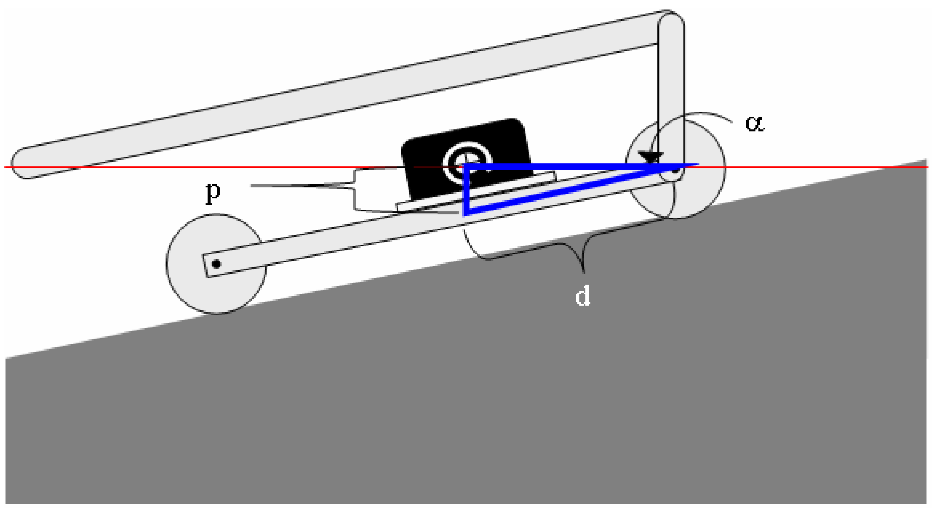

Figure 2.2. Measurement Concept of the UTA Pushcart Profiler.

Once this device was operational, various experiments were run, checking angle values and running the instrument along the laboratory floor in the Transportation Instrumentation Laboratory (TIL) at the University of Texas at Arlington. Both a gyroscope and inclinometer were used for the measurement sensor. The main components of the UTA Pushcart Profiler are shown in Figure 2.3. The components shown in this figure includes a notebook computer with an A/D unit for capturing the raw gyroscope sensor data, a signal module which contained the power converter and electronics for the unit, a Watson Inc. gyroscope, a distance encoder for determining distance traveled, and a battery. Test runs were also made in the hallway outside of the

TIL lab and in the parking lot behind Nedderman Hall at UTA. The design of the pushcart was then sent to TTI researchers, and a newer version of the pushcart was made for testing. Figure 2.3 provides a diagram of the electronics of the unit used. For the unit, the platform was free to move up or down, measuring the slope of the pavement traveled using either a gyroscope or inclinometer. A notebook using a DT 9803 module from Data Translation along with an updated program for real-time measurements were added to provide the bump measurements.   A functional diagram of the principal components are illustrated in Figure 2.4.

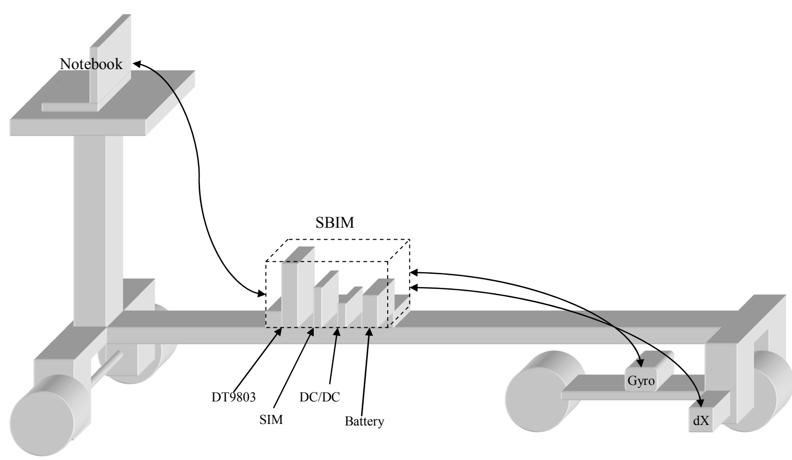

Figure 2.3. UTA Pushcart Profiler.

The Pushcart Test Runs

The new unit was then used in test runs at the Texas A&M Riverside Campus in 2003. Data were collected using this device on the outside wheel path of an overlaid test section at Runway 35L. Runs were made during the summer and fall of 2003. Two of the data runs made in August were good. However, problems with the battery and PC hampered the remaining runs. The runs (528 feet in length) were made in both the north and southbound directions on the same wheel path, and the data were compared to the reference profile. The results of the August runs are illustrated in Figure 2.5, along with the reference profile, after the test profiles were adjusted using the beginning and ending elevations along the reference profile. In October of the same year, six more runs were made in the northbound direction and five runs made in the southbound direction using the pushcart profiler. Figure 2.6 illustrates the results from the October runs. As noted, the results in August followed the reference profile more closely. However, the October runs did not repeat as well, nor were they as close to the reference profile. Some of this difference could be explained by the fact that the cart was pushed at normal walking speed in October, not giving enough time for the gyro instrument to accurately measure the platform angles. The runs done in August were taken at a much slower pace. It should be noted that the sliding profiler would be operated at a very slow speed on concrete paving projects, so researchers were hopeful that more accurate angles could be measured when the measurement concept was used with the sliding profiler.

During a later meeting, it was decided that the system should be more concerned with bumps, rather than accurate long wavelength profile. Thus efforts were focused on developing a means of measuring bumps rather than profile for the sliding profiler. The next chapter discusses the development of the sliding profiler.

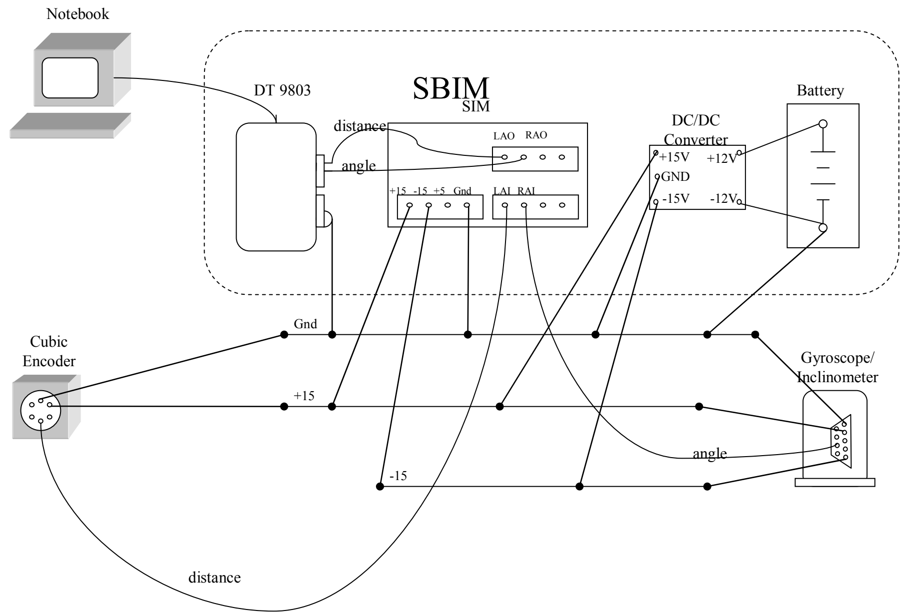

Figure 2.4. Functional View of Main Components of the Pushcart.

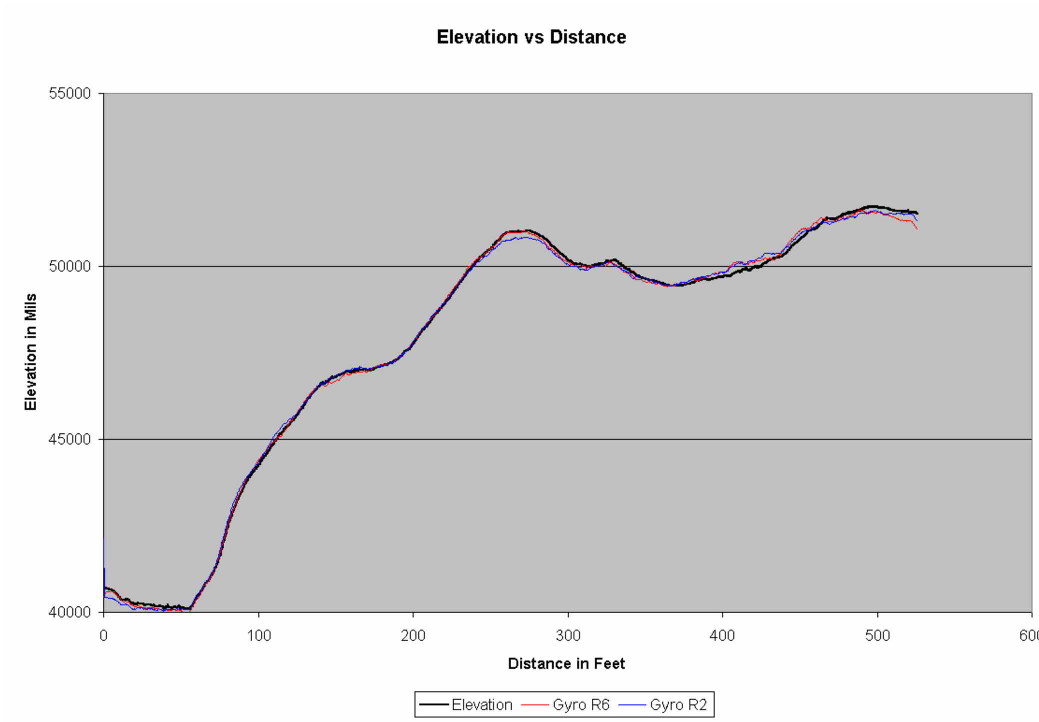

Figure 2.5. August Data Runs Using Pushcart Profiler.

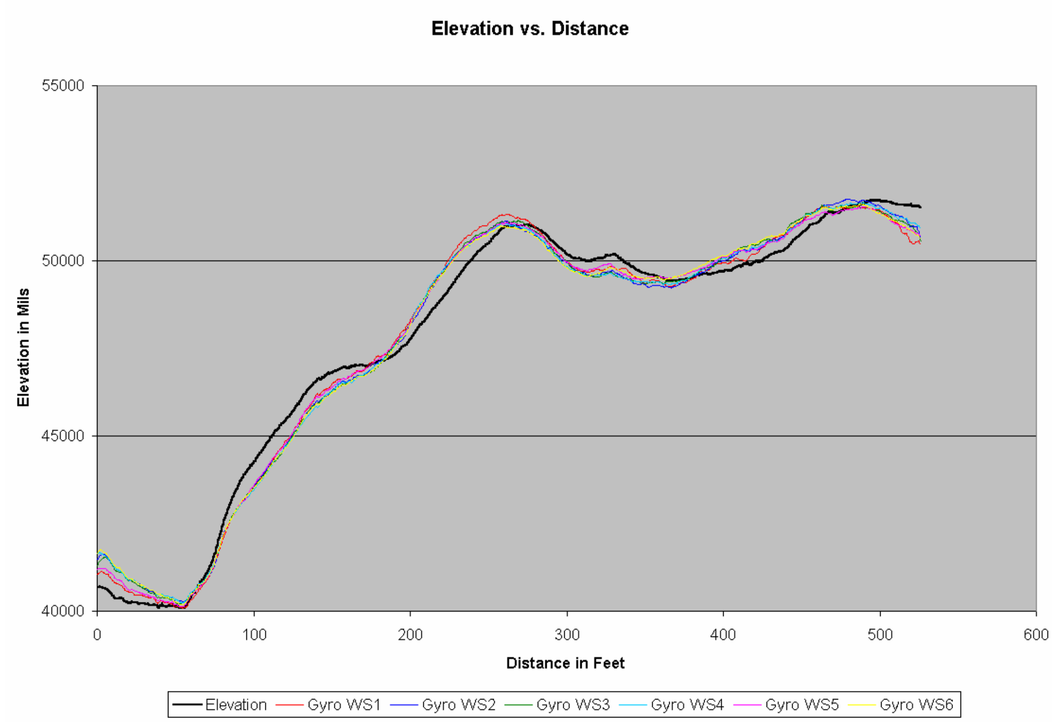

Figure 2.6. October Data Runs Using Pushcart Profiler.

CHAPTER 3
SLIDING PROFILER DEVELOPMENT

Introduction

During the project site visits, researchers sought to identify methods for detecting bumps that would not disturb the wet concrete while it was being placed. The Ames device used three laser sensors to measure the displacements between the wet concrete and a beam extending out from the paving device. Since each laser costs much more than all of the components of the sliding profiler put together, the sliding profiler could potentially provide a much cheaper alternative for detecting bumps during paving. The construction and testing of the sliding profiler is discussed in this chapter.

The idea of using the original UTA pushcart concept for measuring bumps on newly poured concrete was based on observations of the autofloat while visiting construction sites during Phase I. In trying to come up with a method that could measure the profile of wet concrete, yet be somewhat detached from the paving unit, researchers came up with the idea of using a ski-like device similar to the autofloat ski (see Figure 3.1) that could hold the necessary components and sensors. The unit would then float or slide along the wet pavement behind the paving train.

The basic concept of the sliding profiler is illustrated in Figure 3.2. This figure shows a conceptual illustration of the system for locating defects during placement of concrete. The profiler electronics are housed inside a box that is mounted on a ski similar to the autofloat ski used on construction projects (there is a picture of the autofloat ski shown in the background of this figure). The ski uses a distance encoder on a wheel, which also travels along the wet concrete. Data from the profiler is transmitted through a wireless local area network (LAN). The operator will be able to view measurements made with the profiler using a portable notebook computer, which will report bumps detected by the system and their locations for correction by the finishers at the site.

Figure 3.1. Autofloat Attached to Paver.

The sliding profiler concept developed by researchers involved using a ski similar to the one shown in Figure 3.1 yet that functioned in a similar manner as the pushcart illustrated in Figure 2.3. As was noted in Figures 2.6 and 2.7, the pushcart gave profile readings closer to the reference when it was pushed along the test path at a slower speed since more time is available for the gyroscope or inclinometer to settle and give more accurate readings. This slow operational speed is compatible with the speed at which the paving train moves on PCC projects. Thus, researchers expect that the sliding profiler concept should work for this application. Additionally, since the sliding profiler would be on wet concrete, researchers initially planned to have the data sent to a handheld PDA, small computer, or notebook via a wireless link. If an inclinometer were used in placed of the gyro, the electronics cost per wheel path of such a system would be low relative to laser-based devices, less than a couple of thousand of dollars per unit. However, materials and fabrication costs would have to be added to the cost of the electronics.

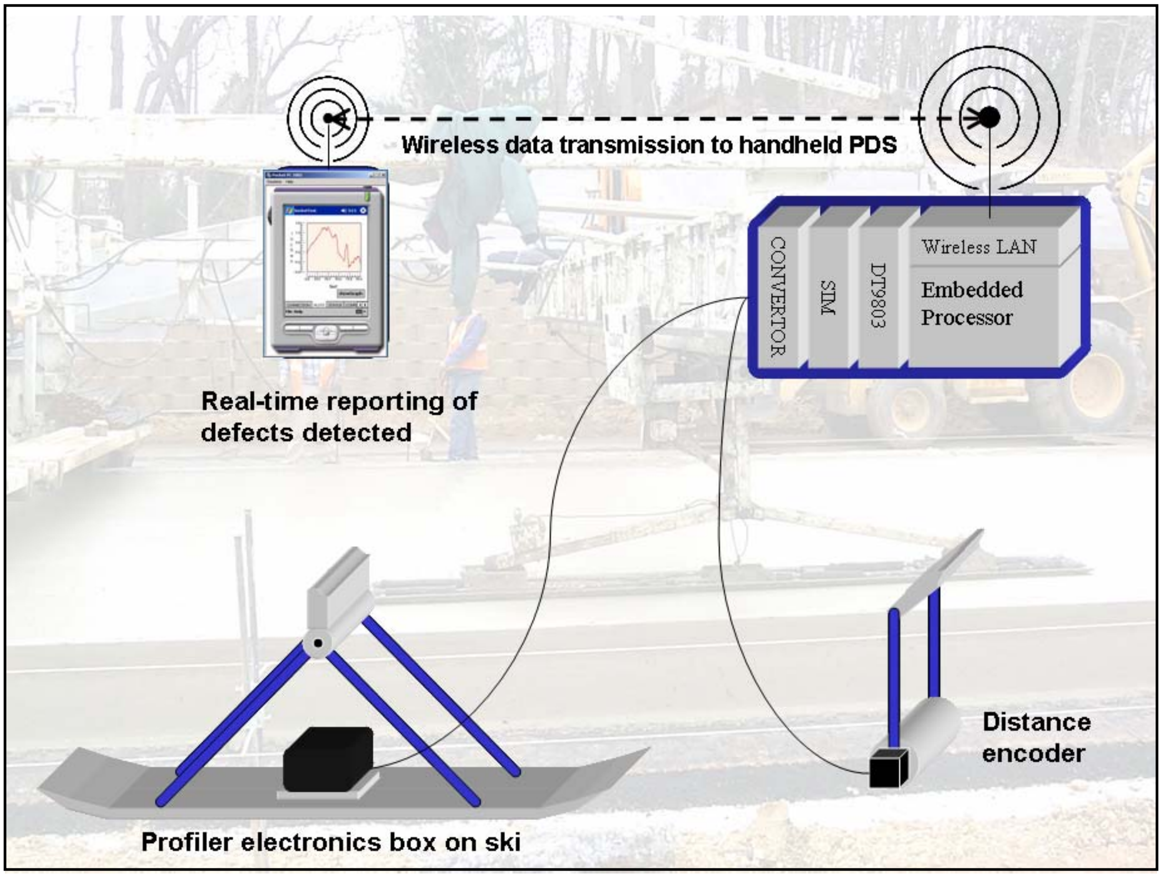

Figure 3.2. Sliding Profiler Concept.

Sliding Profiler Development

During the project, researchers met with a number of contractors to discuss the concept of early bump detection during placement of wet concrete on Portland cement concrete projects. These visits identified relevant criteria researchers considered in development of an instrument for quality control of concrete smoothness.

The comments received reflected a general consensus on the following needs:

- glides on wet concrete;
- priced affordably so that contractors may purchase multiple units to monitor the wheel paths of the travel lanes and to check the work of finishers, as necessary;
- easy to use;
- made of rugged workmanship to handle rigors of the construction environment (machine vibrations, water sprays, chemical retardants and others);
- mounts on existing equipment; and
- shows defect locations.

A bump detection instrument that glides on wet concrete implies a method of measurement where the instrument is in contact with the surface being tested. Researchers took this approach for two reasons:

- to develop an alternative to the Ames RTP, which was undergoing development and testing at the time of this project; and
- to develop a method that is affordable to contractors.

As mentioned above (also see Appendix B), Ames Engineering was already testing a system consisting of three lasers for measuring profile on wet concrete. In addition, Gomaco was developing its "wet profilograph" to provide a similar capability but for measuring bumps. Both of these methods are based on non-contact measurements using lasers for the Ames Real Time Profiler and acoustic sensors for Gomaco's wet profilograph. Because of these on-going development efforts, this project further investigated the sliding profiler concept to provide an alternative method that does not duplicate existing efforts elsewhere and provide contractors with more choices for quality control of surface smoothness on concrete paving projects. As originally conceived, the sliding profiler concept involves contact measurements of surface profile with a ski-type box instrumented with sensors that measure slope and distance, and supporting hardware and software for data acquisition and real-time data processing. Since a slope sensor is used in lieu of multiple lasers for elevation measurements, significant savings in instrumentation cost would be realized, making the unit more affordable to permit multiple sliding profilers to be deployed on a paving project. This profiler would be pulled behind the paver and would easily mount on existing equipment, as illustrated conceptually in Figure 3.3.

Initial Sliding Profiler Design

For the concept to be useful in practice, the sliding profiler needs to slide on the surface being tested. To accomplish this requirement, the profiler has to be of such a design that it will not sink under its own weight nor dig into the fresh concrete as it is pulled behind the paver. Thus, researchers sought to minimize the pressure on the fresh concrete due to the weight of the profiler and have rounded edges on all four sides of the contact surface.

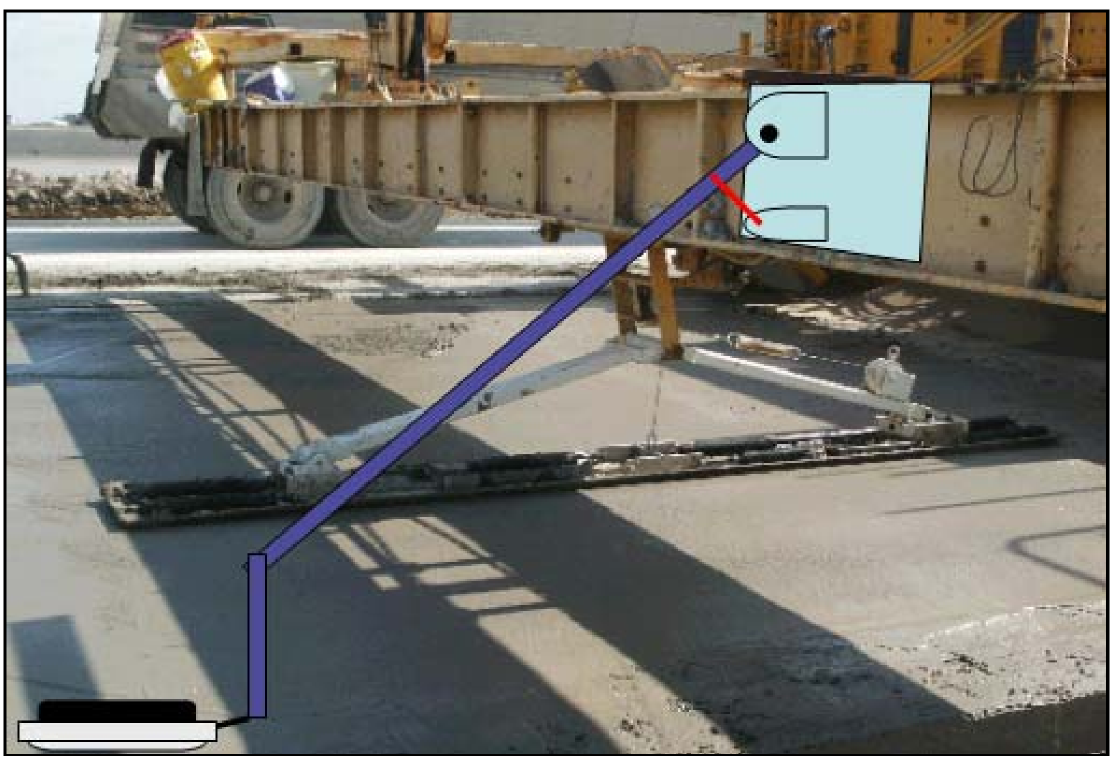

Figure 3.3. Conceptual Illustration of the Sliding Profiler Being Towed by the Paver.

The total weight of the sliding profiler consisted of the weight of the housing unit plus the weights of the individual components within the profiler box, which consisted of the inclinometer, a data acquisition board, an embedded microcomputer, a power supply module, a 12-volt battery, a wireless communication device, and the mounting plate for the electronic components. In addition, the sliding profiler included a subsystem for distance measurement, consisting of a distance encoder attached to a pair of wheels. Most of the profiler's weight came from the mounting plate and the 12-volt battery.

Figure 3.4 is a picture of the sliding profiler that researchers first fabricated and tested in this project. In this initial development, researchers adapted a chafer pan as the housing unit for the profiler components. Since no custom molding had to be made, only a minimal amount of machining was spent to put together the initial sliding profiler.

Figure 3.4. Initial Sliding Profiler Fabricated in this Project.

At the suggestion of the project coordinator, researchers assembled a sand box for testing the profiler design. The box researchers used is approximately 4 ft wide by 32 ft long. It is filled with sugar sand, a very fine, cohesion-less material that proved useful for checking whether the profiler will likely glide on fresh concrete or dig into it before a trial run is ever made on a concrete project. Figure 3.5 shows the initial profiler being tested in the sand box.

In these tests, the researchers sought to verify whether the housing unit might be expected to perform satisfactorily on fresh concrete. The weight shown on top of the housing unit in Figure 3.5 simulates the weight of the components inside the profiler box. As may be observed, the tests did not go well for this initial design. The profiler tended to dig into the sand, as is evident from the build up of material in front of the unit. Consequently, researchers sought to modify the initial design to correct this behavior.

Figure 3.5. Sand Box Testing of Initial Sliding Profiler.

Modifications to the Initial Sliding Profiler

Because of the tendency exhibited by the sliding profiler to sink in the sand box tests, researchers modified the initial design by increasing the contact surface area. At first, researchers fabricated a sled and performed tests with the sliding profiler on a parking lot job for an apartment complex that was being built in Bryan, Texas. In these tests, the sliding profiler was placed on the sled, which was then pulled across the fresh concrete surface, as illustrated in Figure 3.6. As may be observed, the sled performed satisfactorily. It did not dig into the concrete surface at any time during the tests. However, researchers observed that the wheels for distance measurement tended to pick up fresh concrete, as is evident from the wheel tracks left by the profiler in Figure 3.6. This observation was a concern since the accumulation of fresh concrete on the wheels (Figure 3.7) could significantly affect the distance measurements, particularly on a paving project where the sliding profiler would be operated over much longer distances compared to the interval covered in the tests conducted. To address this concern, researchers considered other options for distance measurement. From this consideration, researchers decided to go with the setup shown in Figure 3.8.

Figure 3.6. Test on Fresh Concrete with Sliding Profiler on Sled.

In this setup, researchers fabricated a measuring wheel out of a 4-inch PVC tube. The wheel was turned at the machine shop to ensure roundness and to add a slight texture to the polished surface. Researchers also added a floating squeegee to clean the wheel during testing and prevent the accumulation of wet concrete on the wheel surface. In addition, researchers moved the distance encoder into the housing unit and, thus, have all sensors protected from the operating environment.

The housing unit itself was changed. In lieu of the chafer pan, researchers fabricated a new box to house the sensors that consisted of the sled shown in Figure 3.6 and a matching cover. All electronics were moved from the chafer pan into the sled that now formed the bottom half of the housing unit.

A final change affected the way by which the sliding profiler was connected to the paver. Originally, the sliding profiler was envisioned to be pulled behind the paver through a rope or chain, as illustrated in Figures 3.3, 3.5, and 3.6. However, because of pavement cross-slope, researchers found that the profiler would slide off the test wheel path and run skewed with this arrangement. Consequently, researchers fabricated new hardware for connecting the sliding profiler to the paver.

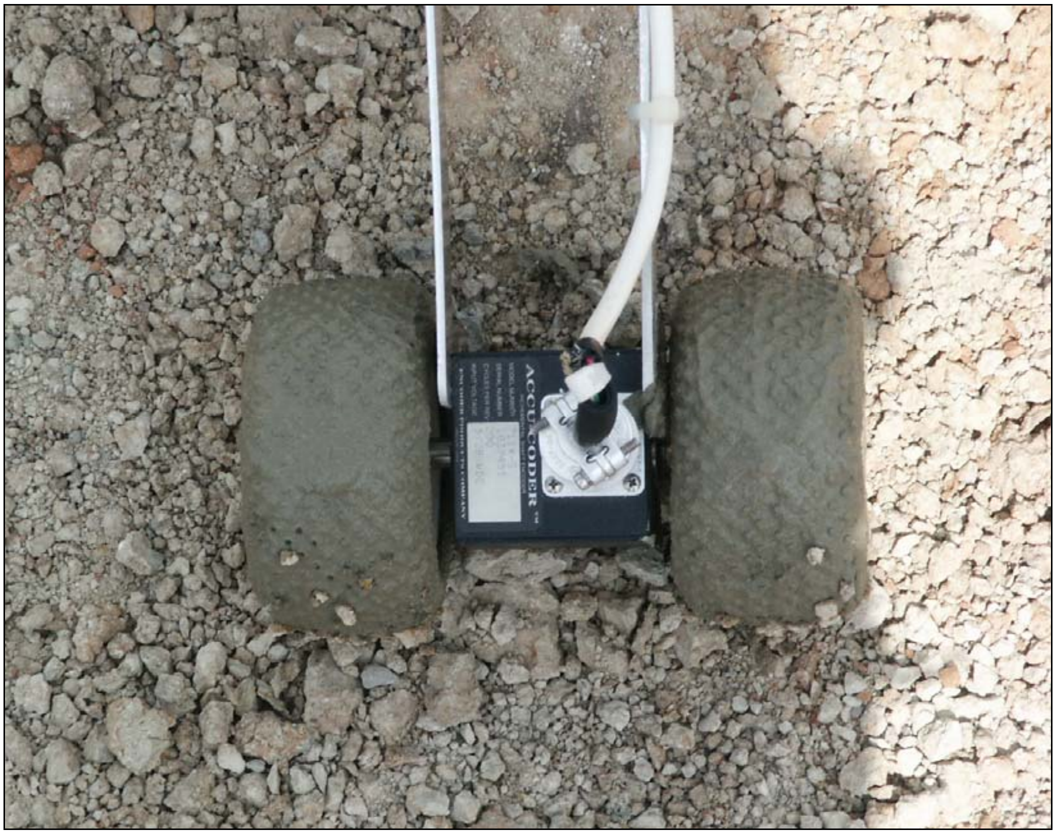

Figure 3.7. Concrete on Measuring Wheels.

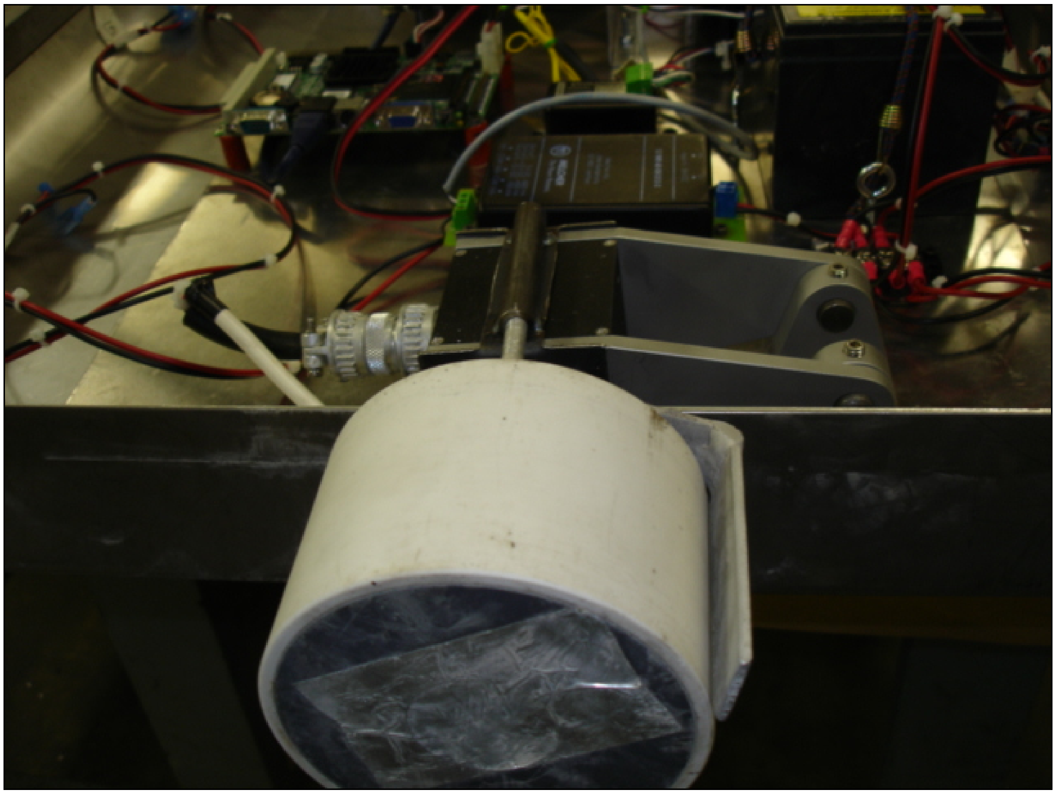

Figure 3.8. Picture of Modified Distance Measurement Subsystem.

Figure 3.9 shows the prototype sliding profiler developed in this project. The picture shown was taken from a test conducted on a PCC paving project along I-20 in the Fort Worth District. It illustrates how the profiler is attached to the paver. The angled bracket in the picture is a telescoping rod that permits adjustment of the distance between the profiler and the paver. On this particular job, the profiler was positioned so as not to interfere with the operation of the autofloat finisher, which is partly visible on the left side of the picture. The vertical bar connecting the profiler to the angled bracket is spring loaded and hinged at the bottom. This arrangement helps to keep the profiler on the test wheel path while permitting pitching motions due to the longitudinal profile of the surface being placed.

Figure 3.9. Prototype Sliding Profiler Tested on I-20 Project.

Test of Prototype Sliding Profiler on I-20 Project

As indicated previously, researchers tested the prototype sliding profiler on a PCC paving project along I-20 in the Fort Worth District. Tests were conducted on a segment of the construction project located just west of the US 281 junction near New Salem (see map on Figure 3.10). Prior to the start of paving operations, researchers set up the instrument as shown in Figure 3.9. Once construction began, the profiler was pulled along the existing concrete surface, across the header joint, and onto freshly placed concrete, as illustrated in Figure 3.11.

Researchers monitored the sliding profiler and observed throughout the test that the profiler slid smoothly along the wet surface and that the floating squeegee performed its function of cleaning the distance wheel. These observations are illustrated in Figure 3.12. Note the concrete being wiped off the wheel at the bottom of the squeegee.

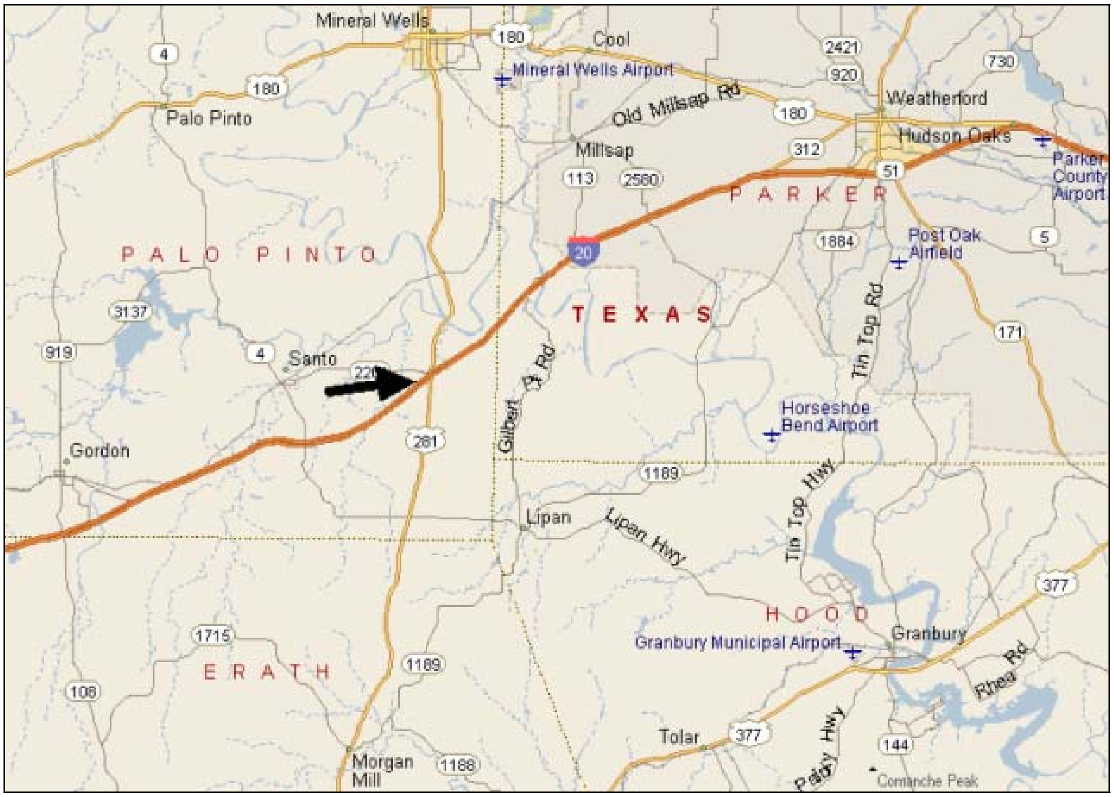

Figure 3.10. Map Showing Location along I-20 of Sliding Profiler Tests.

Researchers also monitored the temperature inside the sliding profiler during the test through a thermal probe connected to the embedded microcomputer board inside the unit. These measurements showed that the temperatures inside the profiler varied from 94 to 107 ºF, which are within the operating range of the electronic components used with the profiler. However, researchers note that the weather was not particularly hot on the day the test was conducted, with air temperatures ranging from the upper 80s to the mid-90s.

Figure 3.11. Photo of Sliding Profiler Taken Just after Crossing the Header Joint.

Throughout the test, the sliding profiler was powered through the battery inside the unit. The profiler was operated for about five hours. All data were collected via wireless communication. For the purpose of collecting reference data to evaluate the results from the sliding profiler, researchers marked segments along the project tested on which elevation measurements were later taken with the Walking Profiler and the rod and level.

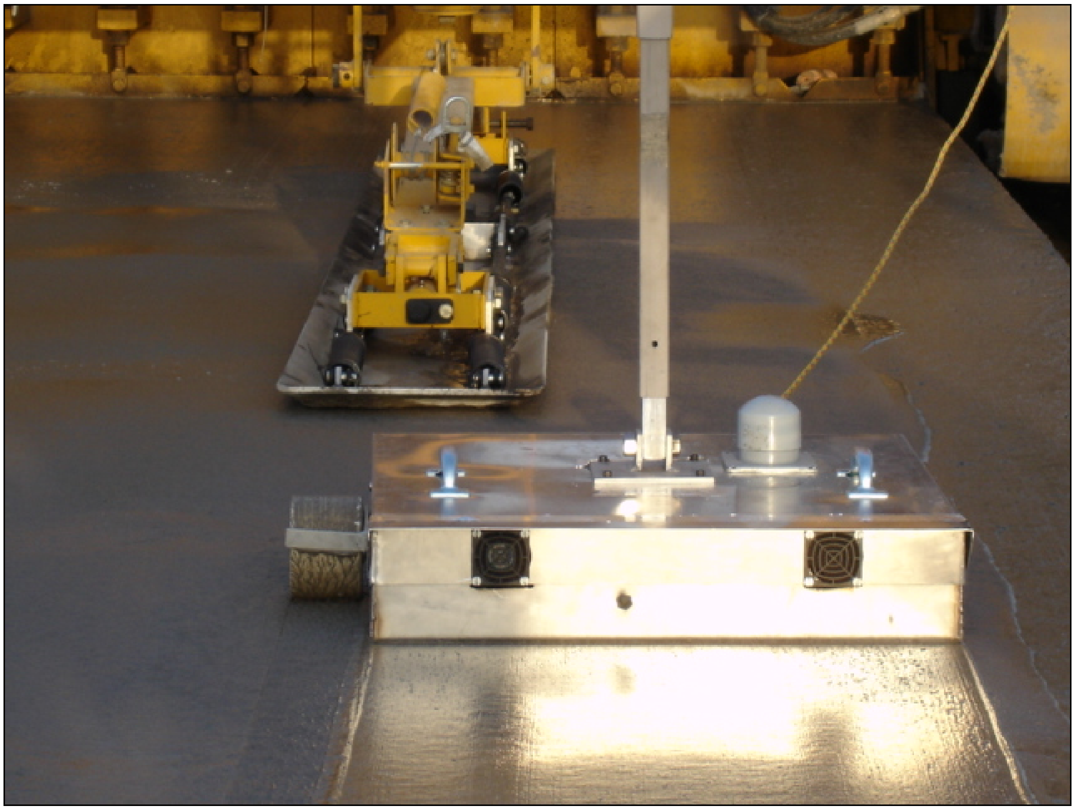

Figure 3.12. Photo of Sliding Profiler during Test along I-20 Project.

Figure 3.13 shows the Walking Profiler used to collect unfiltered elevation data on selected sections of the project tested. For these tests, elevation measurements were taken on about the same path tracked by the sliding profiler, but after tining and hardening of the concrete slab (approximately two weeks from the time of the sliding profiler test).

Figure 3.13. Walking Profiler Used to Collect Reference Elevation Measurements.

The Walking Profiler runs were broken into sections. Since these measurements are relative to the elevation of the starting point, researchers took rod and level measurements at specified intervals along the project and used the rod and level data to tie the elevation readings from the Walking Profiler to a common benchmark.

Figure 3.14 shows the longitudinal profile determined from the Walking Profiler and rod and level measurements made on sections F8, F9, and F10 of the project tested. For each section, three repeat runs (A, B, and C) of the Walking Profiler were made. In the following, researchers verify the results from the sliding profiler against the reference elevation measurements. The comparisons of the sliding profiler measurements with the Walking Profiler reference profile after adjusting the beginning and end points with the reference profile are illustrated in Figure 3.14. Although the profile did not follow the reference profile as well as the August pushcart comparisons discussed in Chapter 2, researchers were encouraged with the results, considering the possible errors in the comparison process.

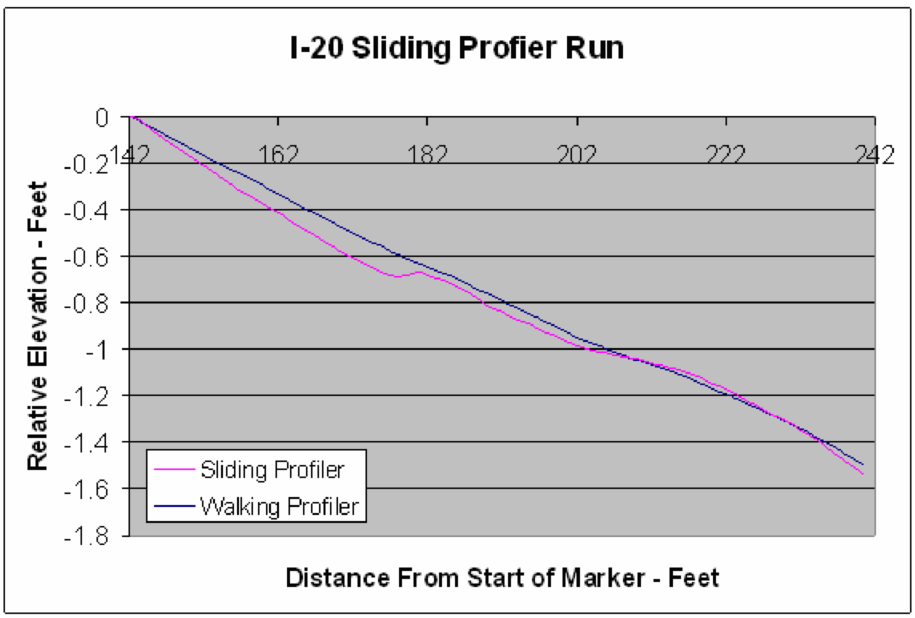

Figure 3.14. Longitudinal Profile Determined from Walking Profiler.

The Walking Profiler is used after the concrete has been allowed to dry. Any changes in the concrete as it dries could result in differences. This was the first time the device was actually used on a paving project, and to prevent loss of data for any reason, the measurements were broken into approximate 100-ft sections. This was also done in the event the distance encoder wheel did not rotate, thus preventing accurate distance measurements. In the process, the program would restart and occasionally miss a short section so the exact starting place of each set could not be precisely lined up with the reference profile runs. The Walking Profiler runs were made as close as could be recalled to the runs made by the sliding profiler. However, it was not possible to exactly line the two profiles. The sliding profiler was pulled behind the auto float, but before the finishers and many of the bumps would have been fixed and the surface of the pavement slightly changed. The surface was then carpet dragged and tined, further changing the surface.

Data Acquisition and Sliding Profiler Program Procedure

The program procedure for acquiring sensor data and profile processing was a simple program written to acquire and save the raw data for later processing. Since it was only written as a means to collect data, it will only briefly be described. The data acquisition process was divided into two parts. The first is the data acquisition server. A client program initializes the server, sending data acquisition parameters to the server in accordance with the operator commands. The client program also writes the data to a file so that a separate analysis program can process the data to compute the profile and/or bumps. This procedure provided two advantages. First, it allowed researchers to insure that good sensor data were being collected and recorded. Second, it allowed for flexibility in comparing or perfecting the processing methods. To get around the lack of a real-time platform, researchers used Windows 98 as the data acquisition server platform, with a number of its features removed so that it would fit into the flash memory of an embedded PC. UTA researchers had used the Windows 98 platform for running WinTK, the server program developed by UTA for updating the TxDOT profiler. Thus, considerable experience existed in using this same platform, and, in fact, much of the code needed for sending the data to the client was extracted from WinTK. The data acquisition server and recording client programs were written in Visual C++, which supported wireless and Ethernet sockets. A wireless network hub was placed on the sliding profiler for communications between the client and server when the sliding profiler was on the wet concrete. A plastic dome was added to the sliding profiler to allow the signal from the antennae to broadcast out to the job site. The acquired data were sent via Ethernet sockets from the server to the client program located on a laptop running under a Windows XP platform. Finally, after the data had been gathered, a Matlab program was used for performing the analysis computations.

Sliding Profiler Data Server and Client Modules

The data acquisition server uses a Data Translation 9803 A/D module for acquiring the analog sensor data and converting the data to digital form. The main components of the system are illustrated in Figure 3.15. Data Translation™ provides the necessary device drivers needed for the A/D Module for Windows platforms (See Figure 3.16). The server program is divided into three primary threads that perform this process.

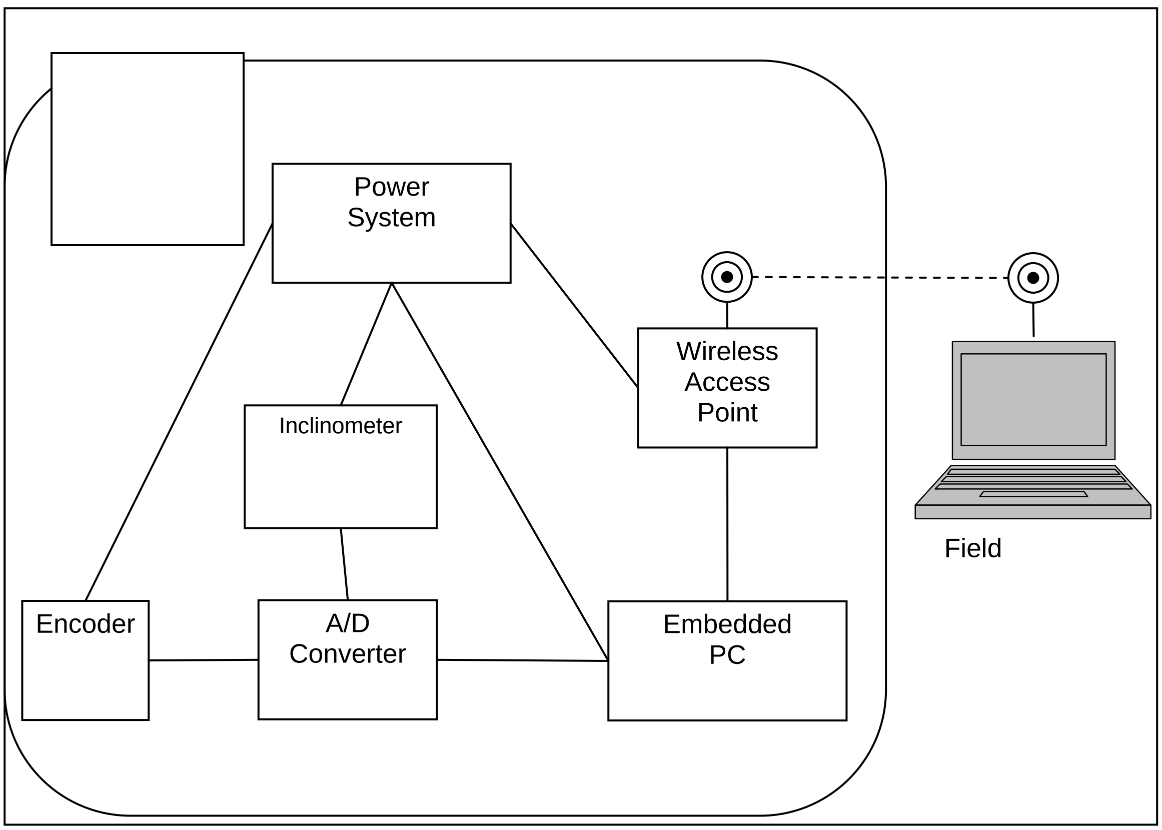

Figure 3.15. The Sliding Profiler Data Acquisition System.

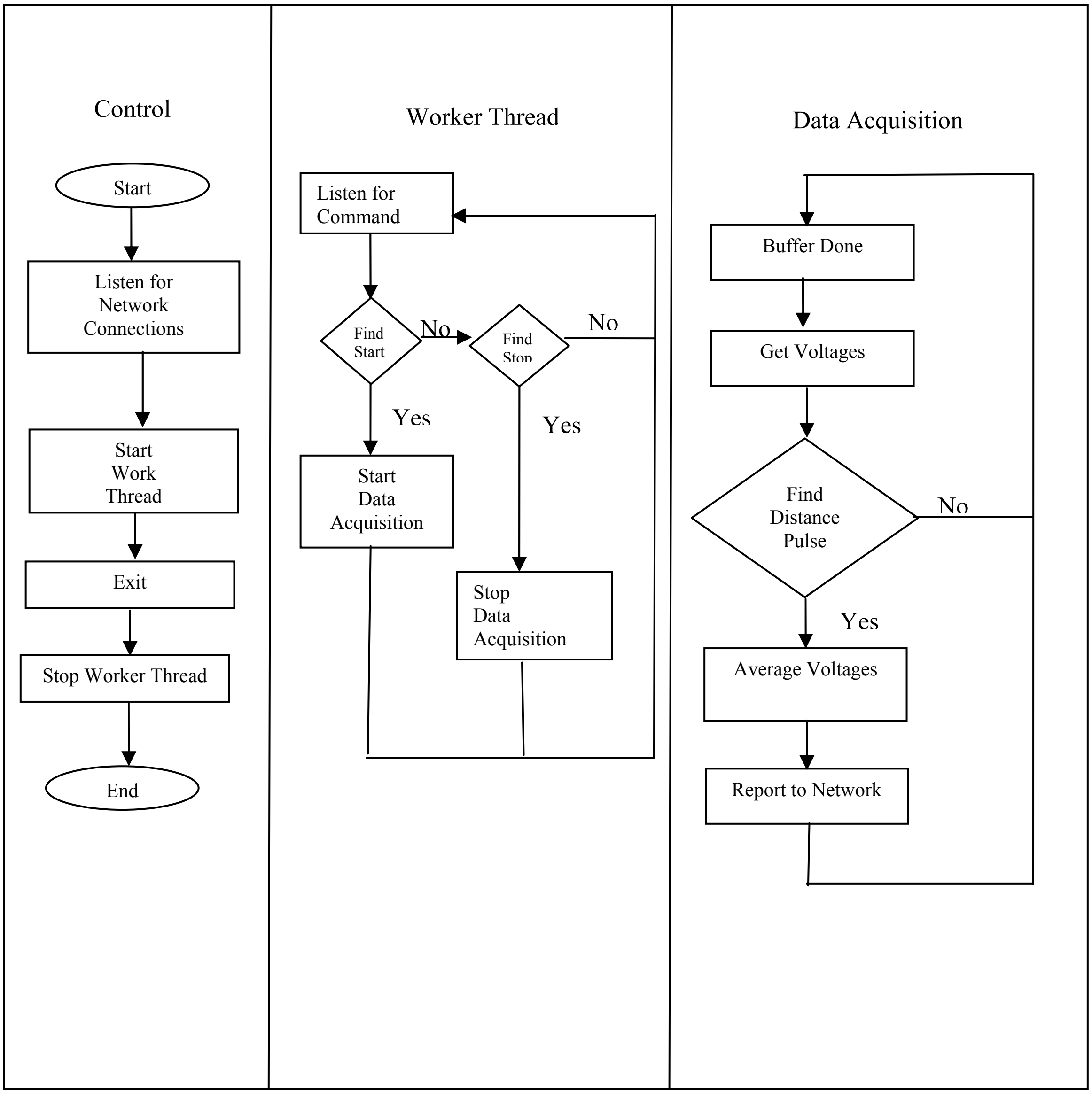

Figure 3.16. Data Acquisition Server Program.

This multi-threaded program both listens to the network commands from the client and communicates with the client program, running under XP. The functions performed in each thread are illustrated by the flow diagram in Figure 3.16.

The Data Recording Client program is a simple communications program receiving data acquisition and recording commands from an operator, sending the appropriate commands to the acquisition server, and saving the data received from the server to a file. The flow diagram for this client is illustrated in Figure 3.17. An initialization file is used for the two programs to provide the various parameters needed for operations. The client receives commands from a user or operator for controlling the process. These commands include sending the initialization data over to the server, starting and stopping the data collection and the server, and specifying where to save the data file.

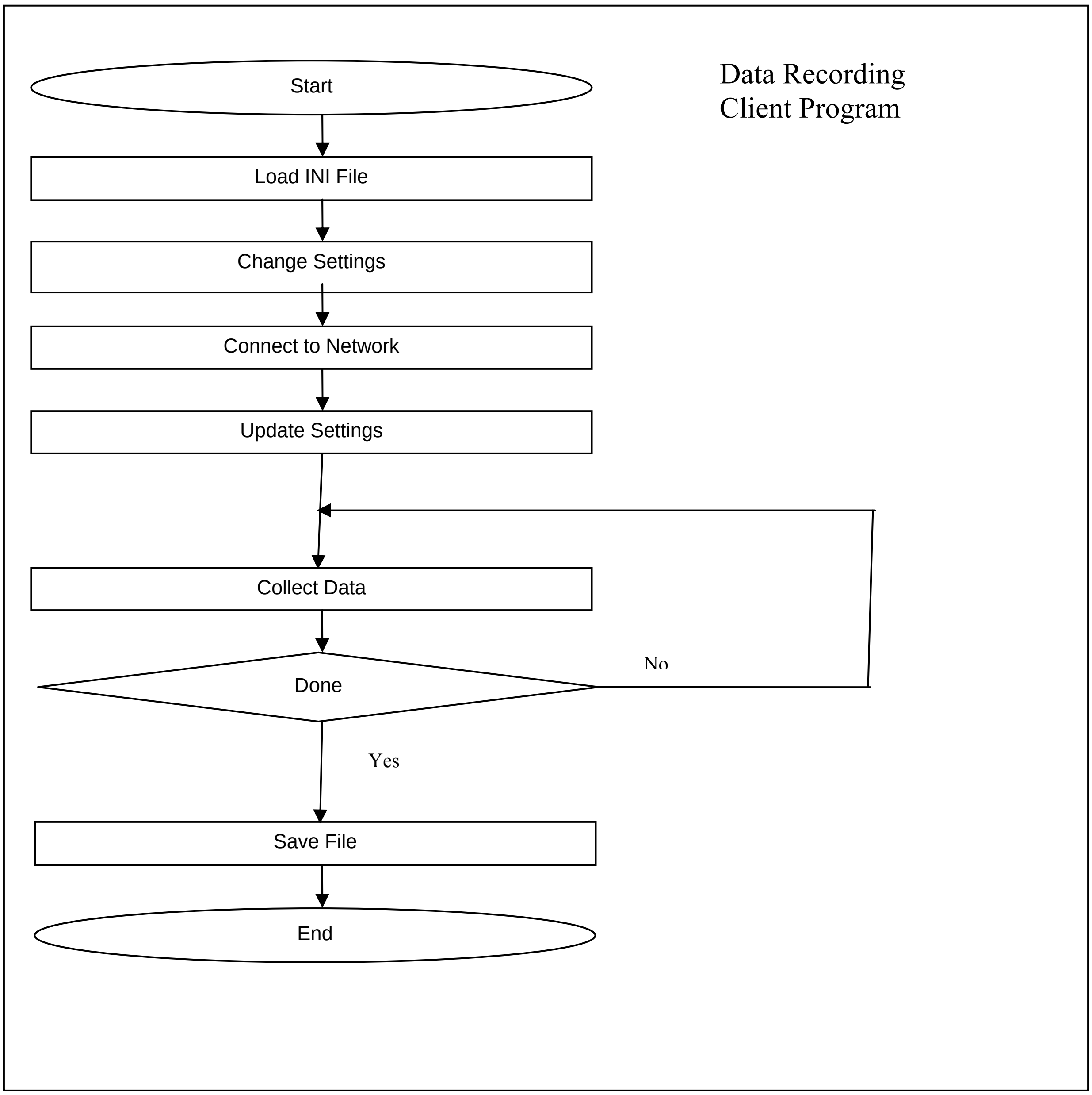

Figure 3.17. Flow Diagram for Data Recording Client.

CHAPTER 4
SUMMARY AND CONCLUSIONS

The primary objective of the research discussed in this report is to identify a suitable device for bump detection on newly poured concrete that will be consistent with the current ride specification. During the first year of the research, existing practices for building smooth concrete pavements were investigated, site visits to various ongoing construction projects were made, and current instruments or procedures for early bump detection were investigated. The research also included an extensive survey of what would be needed for such a device. This effort is discussed in Chapter 1 and Appendix A.

Researchers identified two companies that were working on possible units. Gomaco was developing a "wet profilograph," but it was not ready for demonstration. Ames Engineering was working on a device called the Real Time Profiler, which had been tested on several construction projects. The Ames device used three lasers that were moved along the pavement and used to measure the displacement between the laser and the pavement. It was viewed at a site visit to Ames Engineering. To have an alternative method of early bump detection that would be much cheaper than a laser-based method, the decision was made to investigate a modified version of the UTA low-speed pushcart profiler that was developed on an earlier project. Researchers came up with the idea of a floating or sliding profiler that would implement the same method as the earlier pushcart.

Because of the status of the Ames unit, its progress was monitored and one of the prototype devices rented for evaluation at the Texas A&M Riverside Campus. This evaluation is presented in Appendix B of this report. Researchers then built the sliding profiler to test its use for early bump detection on wet concrete pavements. The construction efforts and testing of this device were discussed in this report.

The Ames unit focuses on computing pavement profile and is attached to the paver. The measuring sensors of the Ames device are three lasers, placed longitudinally along the direction of travel, typically along one of the wheel paths.

The sliding profiler concept is much less expensive, using a sensor attached to a ski that slides along the concrete behind the paver or finishers. It estimates the profile to detect bumps along the path of travel. It can be attached to the paver, autofloat, or work bridge. This device will allow TxDOT contractors to locate and fix bumps while the concrete is still fresh. The implementation of this device will improve the general smoothness characteristic of CRC pavements. This device can minimize, if not eliminate, the need to use grinding operations to improve the riding quality of CRC pavements, thus reducing contractor cost.

Recommendations

The sliding profiler concept has been tested with limited verification. Researchers recommend that further verification be made on construction jobs in a follow-up project. Runs before and after the finishers where defects are detected would help verify whether the sliding profiler is properly identifying bumps and demonstrate its usefulness to contractors. Comparisons with the Walking Profiler over sections where the sliding profiler was used or not used could provide information on its usefulness in locating bumps or dips. Comparisons with bump profiles from the sliding profiler and reference profile is needed to fine-tune the profile/bump calculation algorithm.

Development of the sliding profiler program and concepts involved three phases: data acquisition, recording, and analysis. The system used for implementation should include a real-time profile computation capability, as well as the addition of GPS so that profile can be compared with reference measurements. An operator control console and interface could be included, along with the bump indicator to report location, height, and width of bump, and to provide a summary of defects found at the end of the day's production.

Additional considerations should be given to the following:

- determine best design and fabrication of production version,
- determine best target hardware and software platform,
- redesign and fabricate sliding profiler carriage, and
- redesign and fabricate profiler mounting system.

A final note to mention is the plans to go ahead and develop a practical implementation of the sliding profiler beyond the current data collection model. A new system is being planned that will have the bump detection algorithm internal to the device. This means the system will be self-contained and will be able to operate without a client program. The new sliding profiler will be able to signal the workers when a bump has been detected

At the time of this report, many of these recommendations have been implemented. A patent is being applied for the device.

APPENDIX A
Survey of Paving Equipment and Site Visits

Introduction

Over the years, smooth road profile has become a standard measure of pavement quality. Smooth roads provide comfort while riding, minimize vehicular wear and tear, and increase pavement life. Nowadays, stringent measures of smoothness are implemented to ensure pavement ride quality. Deviations from acceptable smoothness levels either result in bonuses to the contractor for high quality work that exceeds standards or penalties for sub-standard work. Studies point out that longitudinal roughness contributes to undesirable vehicular discomfort (Harrison et al., 1991). The smoothness of a concrete pavement depends on the base type, vertical and horizontal alignments, grades, pavement type, paving equipment, and concrete mix. To achieve smoothness, consistency is required in concrete delivery, concrete slump and quality, paver movement and vibration, a consistent head in front of the paver, and a very tight and accurately set stringline.

If the roughness of a concrete pavement is in excess of the specified limit, expensive remedial measures such as surface grinding are required. If this roughness can be identified before concrete reaches its initial set, remedial action can be taken by refinishing the entire surface or by localized refinishing. This combination of literature review and site inspection is an effort to study the factors that affect the smoothness of concrete pavements. The paving procedure and paving equipment commonly used are also covered briefly.

Paving Operation

The paving operation in case of concrete pavements consists of transporting the concrete from the plant, placing it with a slip form paver, and finishing it to obtain a smooth surface. Transportation is done with the help of rear dump trucks or a semi-trailer hauling several batches. The concrete is usually discharged on the ground in front of the paver or into the feed hopper. If discharged on the ground, in case of wide roads, discharging is carried out in two bands to evenly distribute the concrete and to prevent buildup and flow of mortar. When the concrete is delivered from a truck mixer, rotation of the drum at great speed before discharge is essential. A truck mixer causes segregation and discharges a greater amount of coarse aggregate and fine gravel at the start of the discharge.

Once the concrete is dumped on the sub-base by a tipper or a feeder device attached to the paver (Figure 1), it is uniformly distributed across the pavement by means of a double-screw (Figure 2) or through-type transverse system with back and forth movement. If the concrete is not uniformly distributed, ride quality may be adversely affected because of unsymmetrical mechanical action (crab running) of the paver, leading to variable compression action on the concrete in place. The concrete is then internally vibrated by a sufficient number of poker vibrators, which makes it more fluid and ready for molding (Figure 3). The pokers are placed in front of the paver such that, under normal operating conditions, they are submerged in the concrete along a transverse line in the upper third of the slab. The pokers are positioned in a center-to-center distance of 50 cm. The placement of the pokers near the edges is very important. Pokers are usually spaced at a distance of 15 cm from the edges, but this distance may vary depending on the type of concrete. Vibration is necessary to fluidize and consolidate the concrete mass and to provide a sufficient amount of fines at the surface for a tight micro finish. The intensity of vibration of the pokers may be varied depending on the consistency of the concrete and the speed of the paver. In the case of dry concrete, the intensity is increased, but the vibration is reduced in the case of plastic concrete for the same speed of the paver. The vibration should cease when the paver stops to prevent concrete segregation. A stiffer concrete with higher intensity of vibration enables better stability at the edges and improved mechanical strength. Optimum vibration is essential because over-vibrating will cause segregation of the mix and under-vibrating will leave voids in the mix. The concrete may be directly molded to its final form by extrusion, or it may be trimmed subsequently to its final form. The sub-base acts as a base form, while the two side forms supported by the paver rest against the base. A top form (either an extrusion plate, a molding pan, or a vibrating beam), and a system of two oscillating floats ensure trimming of any excess concrete. Initial finishing is carried out by any of the different types of equipment available. Then hand finishing is done with a straight edge (Figure 4 and 5). Floating is then performed to achieve a smooth finish with the help of long-handled floats.

The paver moves on caterpillars, usually connected to the frame by hydraulic jacks, and uses either the sub-base or the guide wires to seek grade. When guide wires are not used, the paver works on the basis of the sub-base profile, or uses the conveyer tracks as reference. Hence, the conveyor tracks should have good surface profile. In case of guide wires, one or two wires are stretched parallel to the alignment of the road with sensors mounted on a cross arm ride on the wire. Any deviation from the equilibrium position generates a signal making the jacks act, either way, to compensate the movement. Since the wires act as the only reference for the profile of the finished slabs, care should be taken to see that the wires are properly leveled, fixed, and pulled taut.

Insertion of dowel bars is carried out in case of jointed concrete pavements to transfer loads in between the sections. There are two methods for inserting the dowel bars. In the first method, cradles holding dowel bars are fixed to the sub-base right along the future joints. In the second method, dowel bars are inserted inside fresh concrete with the help of an on-board dowel bar system at each transverse joint. After insertion, the position of each joint is marked for relief joint cutting. Behind the dowel bar inserter, initial smoothening is usually provided with a sheet of wet burlap and a rotating bull float, followed by a crew who hand finishes both the surface and the edges of the slab. Most of the discussion in the above section on ”Paving Operation" is from a review given by Jeuorges et al. (1996).

Paving Equipment

A number of devices are used in construction of concrete pavements. Researchers reviewed the equipment used and conducted site visits for the purpose of identifying suitable locations where a device for early bump detection may be mounted or installed. There are two basic types of paving equipment used: deck pavers and slipform pavers.

Deck pavers (Figure 8) are generally used for paving bridge decks and embankments. A deck paver consists of the following components, which can be seen in Figures 9 and 10.

- Basic Unit: The deck paver is made up of a basic unit, consisting of a machine frame, which is self-propelled, and the paving carriage, which is mounted on the machine frame.

- Fixed Forms: These pavers require fixed forms to be erected prior to paving. Roller tracks are mounted on the forms to carry the truss. This process does not form and finish curbs.

- Augers: The paving carriage (Figure 8) consists of dual augers, finishing rollers, and a floating pan. The auger system spreads the concrete evenly, and the rollers consolidate the concrete and give the initial finish. The drag pan attached behind the rollers gives the final finish.

- Vibrators: One of the optional attachments available with these pavers consists of spud vibrators, which serve as internal concrete vibrators. These vibrators, when inserted into the concrete, vibrate the mix to eliminate any voids, air holes, or pockets that may have formed during its placement. These are positioned in front of the dual augers.

- Rota-Vibe: Another optional attachment is a patented Rota-Vibe by CMI. It is mounted on the carriage in between the auger and roller system. It uses two freewheeling finned rollers that are adjustable vertically and horizontally to create a uniform concrete surface. It consolidates the concrete and gives a dense concrete mix. It is useful in providing a good finish in case of stiff mix designs.

These deck pavers may be used for paving streets where the curbs are already laid and where the volume of concrete to be handled is not much. Paving using a deck paver is very labor oriented and time consuming; hence, deck pavers are not generally used in highway construction.

Slipform pavers are self propelled and designed to perform placing, consolidation, and finishing of the concrete pavement, true to grade, tolerances, and cross section. Slipform paving trains (Figure 6) commonly consist of the following components:

- Auger System: Once the concrete is dumped on the road surface, the auger system (Figure 2) moves concrete in either direction and spreads it evenly along the width of the pavement.

- Vibrators: These are hydraulically powered and are synchronized with machine movement. The vibrator positioning is hydraulically controlled for ease in start-up and finish operations. The vibrators (Figure 3) help in compaction of the concrete and make it more fluid for easy molding.

- Oscillating Tamper Bar: These are hydraulically powered and are used for total concrete compaction.

- Profile Pan: A profile pan or a molding pan helps in finishing the surface at the required elevation. It consists of a finish pan system, which carries crown for straight or parabolic surface profile. The profile pan forms the surface and edges of the pavement by applying force to the concrete to make it plastic so that it can be molded in the desired geometrical shape. The paving process is supported vertically by the side-forms, which are also part of the profile pan to establish pavement profile. The profile pan automatically adjusts for grade variations during paving.

- Sideforms: These provide lateral support for the concrete during consolidation and prevent breaking of the edges. Sideforms are hydraulically operated and vertically adjustable, providing adjustment of paving depth. Minor paving width adjustments and vertical angle adjustments at the edge of pavement are also possible.

- Finishers: An oscillating surface finisher like the auto float manufactured by Gomaco is generally used for finishing (Figure 7). It consists of a float type blade 12-ft long and 1-ft wide, with a powered apparatus that oscillates the blade front to rear as it travels transversely across the wet pavement. Another piece of equipment that is used to finish the concrete in case of slip form paving consists of a tube mounted on an independent carrier diagonally along the width of the pavement (Figure 4). The tube is dragged back and forth along the concrete surface. It consolidates concrete by its self-weight and gives it a smooth uniform finish.

Site Visits and Telephone Survey

Site visits were carried out on on-going construction projects. The aim of these visits was to identify commonly used equipment and to determine suitable locations for installing or mounting early bump detection sensors on existing equipment. In this way, a prototype that is fully compatible with existing paving practices may be developed and tested. In addition, researchers conducted a telephone survey of equipment manufacturers to determine availability of early bump detection devices, or whether such devices are currently under development.

Site Visits

As given in the work plan, researchers visited six Portland Cement Concrete paving projects. Two of these projects were located in the Dallas District (along the George Bush Turnpike and IH 35 in Dallas); one in the Fort Worth District (along Trinity Boulevard); one in the Houston District (along a frontage road on US 59 in Houston); one in the El Paso District (along IH 10); and one in the San Antonio District (along IH 10 in San Antonio). During these visits, researchers noted that none of the contractors were using a device for early bump detection. One contractor was of the opinion that, since specifications vary between states, it becomes difficult for equipment manufacturers to build equipment that meets the criteria for all states. Regarding placement of sensors for early bump detection, one contractor suggested that the bump meter should be placed behind the paver, and before the finishers, so that they may know when and where to take remedial action to correct defects. Another contractor believed that the sensors should be placed after the finishers to check their work. It may be difficult to mount the equipment on the paver since the vibrations of the motor may affect the measurements. A dedicated unit behind the paver carrying the sensors for early bump detection may be more suitable.

The common pieces of equipment observed during the site visits include a spreader, a paver with autofloat, a carpet drag, and a tining machine. To achieve good ride quality, the spreader and paver are usually run within 50 feet of each other. On hot windy days, the burlap is usually sprayed with a retardant to delay setting of the concrete and aid the finishers. Three different types of finishing equipment were noted during the site visits. An autofloat, supported by cantilever beams attached to the paver, was used for finishing on four of the projects visited. This piece of equipment consists of a ski 12-ft long and 1-ft wide. Its sides are tapered up, to prevent the ski from plowing into the fresh concrete. It is either attached to the paver by means of a cantilever beam (Figure 7), or it may be carried on an independent, self-propelled unit. Another piece of equipment that is used to finish the concrete ahead of the finishers consists of a tube (Figure 4) mounted on an independent carrier diagonally along the width of the pavement. This pushes material to the sides as the tube is dragged back and forth along the concrete surface and gives the concrete a smooth finish. These types of tubes are not in use much because the method requires additional water on slab to work up enough grout and finish the surface. The third type is a mechanical finisher, which is used in deck pavers. It consists of a rotating cylindrical tube attached behind the vibratory unit that finishes the concrete. Usually a square float is attached to the paving machine after the tube (Figure 9). The finisher moves along the width of the pavement as shown in Figure 10. Some contractors also use a rotating tube attached to the rear of the paver. These are not commonly used and are manufactured on a custom basis. After initial finishing by one of the above methods, hand finishing is carried out with straightedges (10, 12, 16, or even 20 feet in length). After this, the contractor runs the carpet drag and/or tiner (Figure 11) on the pavement to give the final texture to the surface. In the end, curing compound is applied on the surface to prevent moisture loss from the slab.

Telephone Survey

In an effort to determine if any equipment for early bump detection is available, researchers conducted a telephone survey of equipment manufacturers. Table 1 lists the manufacturers that researchers called. Except for Gomaco, representatives of the other equipment manufacturers said that no early bump detection devices are available from their respective companies. Gomaco claims that it has a piece of equipment, which it calls a "wet profilograph," for identifying defects during concrete placement. The research supervisor attempted to gather more details regarding the sensors used and the data the instrument provides (specifically, whether it measures surface profile, and the range of wavelengths measured). However, no further details were provided. Researchers also planned to visit with Gomaco representatives, once during the ConExpo Trade Fair held in Las Vegas in March, and again during a visit made by researchers in Iowa in May. However, in both instances, the wet profilograph was not available for demonstration, so the meetings were cancelled.

Recently, the project director provided information on a bump meter being developed by Ames Engineering in Iowa. Researchers met with engineers of the company in May and were given a demonstration of the Real Time Profiler that the company has developed. The RTP consists of three lasers, which may be mounted at the back of the paver in front of the burlap (Figure 12) to measure profile during placement of the concrete. A fifth wheel (Figure 13) is used to measure distance. Although no information is yet available on the performance of the RTP in actual paving operations, test data collected during a trial run on an existing pavement. Over the years, smooth road profile has become a standard measure of pavement quality. Smooth roads provide comfort while riding, minimize vehicular wear and tear, and increase pavement life. Nowadays, stringent measures of smoothness are implemented to ensure pavement ride quality. Deviations from acceptable smoothness levels either result in bonuses to the contractor for high quality work that exceeds standards or penalties for sub-standard work. Studies point out that longitudinal roughness contributes to undesirable vehicular discomfort (Harrison et al., 1991). The smoothness of a concrete pavement depends on the base type, vertical and horizontal alignments, grades, pavement type, paving equipment, and concrete mix. To achieve smoothness, consistency is required in concrete delivery, concrete slump and quality, paver movement and vibration, a consistent head in front of the paver, and a very tight and accurately set stringline.

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- Profile Pan: A profile pan or a molding pan helps in finishing the surface at the required elevation. It consists of a finish pan system, which carries crown for straight or parabolic surface profile. The profile pan forms the surface and edges of the pavement by applying force to the concrete to make it plastic so that it can be molded in the desired geometrical shape. The paving process is supported vertically by the side-forms, which are also part of the profile pan to establish pavement profile. The profile pan automatically adjusts for grade variations during paving.

- Sideforms: These provide lateral support for the concrete during consolidation and prevent breaking of the edges. Sideforms are hydraulically operated and vertically adjustable, providing adjustment of paving depth. Minor paving width adjustments and vertical angle adjustments at the edge of pavement are also possible.

- Finishers: An oscillating surface finisher like the auto float manufactured by Gomaco is generally used for finishing (Figure 7). It consists of a float type blade 12-ft long and 1-ft wide, with a powered apparatus that oscillates the blade front to rear as it travels transversely across the wet pavement. Another piece of equipment that is used to finish the concrete in case of slip form paving consists of a tube mounted on an independent carrier diagonally along the width of the pavement (Figure 4). The tube is dragged back and forth along the concrete surface. It consolidates concrete by its self-weight and gives it a smooth uniform finish.

Site Visits and Telephone Survey

Site visits were carried out on on-going construction projects. The aim of these visits was to identify commonly used equipment and to determine suitable locations for installing or mounting early bump detection sensors on existing equipment. In this way, a prototype that is fully compatible with existing paving practices may be developed and tested. In addition, researchers conducted a telephone survey of equipment manufacturers to determine availability of early bump detection devices, or whether such devices are currently under development.

Site Visits

As given in the work plan, researchers visited six Portland Cement Concrete (PCC) paving projects. Two of these projects were located in the Dallas District (along the George Bush Turnpike and IH 35 in Dallas); one in the Fort Worth District (along Trinity Boulevard); one in the Houston District (along a frontage road on US 59 in Houston); one in the El Paso District (along IH 10); and one in the San Antonio District (along IH 10 in San Antonio). During these visits, researchers noted that none of the contractors were using a device for early bump detection. One contractor was of the opinion that, since specifications vary between states, it becomes difficult for equipment manufacturers to build equipment that meets the criteria for all states. Regarding placement of sensors for early bump detection, one contractor suggested that the bump meter should be placed behind the paver, and before the finishers, so that they may know when and where to take remedial action to correct defects. Another contractor believed that the sensors should be placed after the finishers to check their work. It may be difficult to mount the equipment on the paver since the vibrations of the motor may affect the measurements. A dedicated unit behind the paver carrying the sensors for early bump detection may be more suitable.

The common pieces of equipment observed during the site visits include a spreader, a paver with autofloat, a carpet drag, and a tining machine. To achieve good ride quality, the spreader and paver are usually run within 50 feet of each other. On hot windy days, the burlap is usually sprayed with a retardant to delay setting of the concrete and aid the finishers. Three different types of finishing equipment were noted during the site visits. An autofloat, supported by cantilever beams attached to the paver, was used for finishing on four of the projects visited. This piece of equipment consists of a ski 12-ft long and 1-ft wide. Its sides are tapered up, to prevent the ski from plowing into the fresh concrete. It is either attached to the paver by means of a cantilever beam (Figure 7), or it may be carried on an independent, self-propelled unit. Another piece of equipment that is used to finish the concrete ahead of the finishers consists of a tube (Figure 4) mounted on an independent carrier diagonally along the width of the pavement. This pushes material to the sides as the tube is dragged back and forth along the concrete surface and gives the concrete a smooth finish. These types of tubes are not in use much because the method requires additional water on slab to work up enough grout and finish the surface. The third type is a mechanical finisher, which is used in deck pavers. It consists of a rotating cylindrical tube attached behind the vibratory unit that finishes the concrete. Usually a square float is attached to the paving machine after the tube (Figure 9). The finisher moves along the width of the pavement as shown in Figure 10. Some contractors also use a rotating tube attached to the rear of the paver. These are not commonly used and are manufactured on a custom basis. After initial finishing by one of the above methods, hand finishing is carried out with straightedges (10, 12, 16, or even 20 feet in length). After this, the contractor runs the carpet drag and/or tiner (Figure 11) on the pavement to give the final texture to the surface. In the end, curing compound is applied on the surface to prevent moisture loss from the slab.

Telephone Survey

In an effort to determine if any equipment for early bump detection is available, researchers conducted a telephone survey of equipment manufacturers. Table 1 lists the manufacturers that researchers called. Except for Gomaco, representatives of the other equipment manufacturers said that no early bump detection devices are available from their respective companies. Gomaco claims that it has a piece of equipment, which it calls a "wet profilograph," for identifying defects during concrete placement. The research supervisor attempted to gather more details regarding the sensors used and the data the instrument provides (specifically, whether it measures surface profile, and the range of wavelengths measured). However, no further details were provided. Researchers also planned to visit with Gomaco representatives, once during the ConExpo Trade Fair held in Las Vegas in March, and again during a visit made by researchers in Iowa in May. However, in both instances, the wet profilograph was not available for demonstration, so the meetings were cancelled.

Recently, the project director provided information on a bump meter being developed by Ames Engineering in Iowa. Researchers met with engineers of the company in May and were given a demonstration of the Real Time Profiler that the company has developed. The RTP consists of three lasers, which may be mounted at the back of the paver in front of the burlap (Figure 12) to measure profile during placement of the concrete. A fifth wheel (Figure 13) is used to measure distance. Although no information is yet available on the performance of the RTP in actual paving operations, test data collected during a trial run on an existing pavement match quite well with corresponding data collected using a lightweight inertial profiler (Figure 14). The developers claim that the unit can measure wavelengths up to 200 feet. Unlike an inertial profiler, no accelerometers are used with the RTP. Software included with the equipment plots the measured profile in real time. Additionally, a profilograph simulation may be run on the measured profile to produce a profilogram showing the defect locations. The estimated price of $50,000 provides contractors with a real time profiler to measure one wheel path during paving. Ames Engineering noted that the company would be making a product announcement soon.

Factors Affecting Concrete Pavement Smoothness

Concrete pavement smoothness depends on the base type, vertical and horizontal alignment, grades, pavement type, and concrete mix. A stable and smooth trackline is very important because pavers without an automatic grade control unit rely completely on the stabilized trackline for grade control. In the case of pavers equipped with automatic grade control, an earlier study found that the construction crew might place too much dependence on the automatic control and pay less attention to preparing the trackline, thereby adversely affecting surface smoothness. In a survey done by the Illinois Department of Transportation (LaCroix et al., 1975), pavers without automatic grade control gave better smoothness than those equipped with automatic grade control. Also, a study was done to compare the smoothness of rural and urban pavements. It was observed that pavements in rural sections were smoother compared to pavements in urban areas. Urban sections are shorter than rural sections, requiring more gaps to maintain traffic at cross streets, and, thus, do not lend themselves to high-speed production. There are also more manholes and inlets in urban areas. The type of design did not appear to influence the surface smoothness as the roughness values for reinforced jointed concrete pavements did not differ significantly from the corresponding values taken on continuously reinforced concrete pavements (LaCroix et al., 1975).

To determine the effect of pavement length on smoothness, three different categories were considered:

- under one mile,
- one to three miles, and
- over three miles.

Researchers found that longer projects had better smoothness. It is believed that longer paving projects provide better and smoother production and an opportunity to make minor adjustments in the mixture, equipment, and procedures. Shorter projects, on the other hand, often require more handwork and modifications in the paving trains because of limited space (LaCroix et al., 1975).

While choosing the concrete mix, care should be taken to see that the aggregate gradation is not too harsh and unworkable. This puts load on the machine and creates extra work for the finishing crew, which may also indirectly affect the smoothness (Banasiak, 1996). A steady supply of concrete should be maintained to properly run the paver. Stopping of the paver causes dips and bumps on the surface. In case of stoppages, the area should be recorded for later correction of defects.

The distance between the batch plant and the placement point can also affect pavement smoothness. Dalimier et al. (2001) observed an inverse relationship between smoothness and the distance from the batch plant. He also noted that as the project progresses, the later sections have higher smoothness than the earlier ones. This observation probably reflects the gain in know-how over the construction period and the improvement in logistics to suit the particular project.

Effect of Slab Curling on Surface Roughness

The contribution of curling to measured roughness is significant. Curling induces stress since the pavement is restrained by its weight, as well as the reaction from the subgrade, and causes cracking in the pavement. Early pavement cracking indicates that curling is caused by drying shrinkage and by moisture and temperature gradients across the thickness of slab. Negative drying shrinkage and moisture gradients are usually in slabs on grades, slabs that have been exposed to low humidity air, or slabs where sub-base or subgrade has high moisture content. All these factors cause upward curling in the slab. The positive temperature gradients with its downward slab curling are caused by heat from the sun at the top of the slab. Temperature measurements show that a high temperature differential exists between the top and bottom of the slab. The curing technique could affect the as-built curling, and in turn, the smoothness of a newly placed concrete pavement.

Temperature and moisture conditions at the time of paving and immediately following construction affect curling and warping in PCC pavements. Based on field data collected from Phoenix, Arizona (where the section was paved at night), and Mankato, Minnesota (paved during the day), Rao et al. (2001) observed that daytime paving induced negative gradients that further increased as the pavement underwent drying shrinkage and creep. Researchers also noticed that at the end of two years, upward curling and warping was reduced due to creep. The temperature gradient increased with slab length and reduced with load transfer mechanisms, such as dowel bars and ties.

Analysis of data obtained at the Mankato section indicates a temperature differential of +9.6 °C at flat slab condition. Thus, under condition of zero temperature gradient, the slab will maintain an upward curl equivalent to a curl resulting from a temperature differential of –9.6 °C. The curl cycles with the daily reversal of temperature gradient. It was observed that as the temperature gradient increases, the magnitude of the curl reduces, and vice-versa. Also as the concrete hardens, the slab curling is seen to increase, although the temperature gradient has approximately the same value over the first three days after placement. At zero temperature differentials, the pavement experiences an upward curling due to a built-in temperature gradient. It is seen that the entire slab edges are being lifted upwards because the curl measured at the longitudinal and the transverse edges has a positive value. The edge curling also increases with time. This may be attributed to differential shrinkage and drying shrinkage (Rao et al., 2001).

A preliminary analysis using the finite element program, ISLAB2000, under-predicted the pavement curl. Concrete shrinkage and creep seem to be the apparent reasons for the additional curl experienced by the section (Rao et al., 2001). Also, the section has an underlying open-graded layer, which can cause the slab center to deflect downwards. Since each of the above effects could not be quantified, researchers considered the concept of an equivalent temperature gradient (based on linear temperature gradient). This parameter accounts for the effects of built-in gradients (shrinkage and creep).

The equivalent temperature gradients were computed using the diagonal profile, comparing the elevations of the slab center with respect to the corner at the approach joint. A set of different but closely matching equivalent gradients was determined from different slabs. From Table 2, it is observed that the slab has developed a large amount of curling in the first three days due to plastic shrinkage. The shrinkage gradient alone is equivalent to a temperature differential of –14.9 °C [–22.2 °C − (−7.3 °C)]. During the period between 3 days and 15 days, the dominating effect of creep seems to have reduced the equivalent temperature differential to –14.7 °C. By 40 days, with the concrete gaining additional strength and shrinkage, the slab corners curl back upwards. After two years, the equivalent temperature differential has reduced to –21.9 °C. Long-term creep has reduced the effective curl but has not completely eliminated it.

Analysis of data obtained at the Phoenix section showed a reduced trend of shrinkage and creep compared to the Mankato section, though the section was subjected to a more arid environment with higher humidity at the bottom of the slab due to condensation at night, making it more prone to shrinkage. Also, due to positive built-in gradient, the section did not show a substantial upward curl. It was further observed that presence of dowels and ties reduced the equivalent gradient by 50 percent for the 3-day period and 35 percent for the 40-day period (Rao et al., 2001).

From the above analysis, it can be concluded that the built-in curl developed in PCC pavements depends on the climatic conditions at the time of paving. Also, moisture conditions as the concrete sets can increase the upward curling of the slab. In addition to built-in gradients, moisture and creep effects need to be considered. The equivalent gradients are seen to increase with time, and also with the length of the slab, but decrease with slab restraints. By controlling the time of paving, slab curling may be decreased in the long term (Rao et al., 2001).

Effect of Change in Pavement Curvature on Roughness

Roughness of a PCC pavement changes during daytime. Changes in IRI of up to 0.40 m/km were observed. The change in roughness may be contributed to changes in temperature gradient and its resulting effect on slab curvature. The level of change in roughness depends on structural factors and the slab curvature that was built-in during curing (Karamihas et al., 2001).

A study conducted to measure changes in Mean Roughness Index (MRI) that occurred over a 10-hour period in 11 jointed PCC pavements indicated an average change of 0.20 m/km in the MRI readings. The measurement was conducted starting on a cool morning at 5:07 a.m. and ending at 3:42 p.m. on a clear, hot afternoon. Six of the pavements showed a significant decrease in roughness throughout the day, three of the pavements changed very little, and two increased in roughness (Table 3). A negative value of change in the table indicates that the MRI decreased throughout the day. Further observation of the profiles revealed that the direction of the slab curling did not reverse in any of the pavements. The temperature changes only affected the severity of the curling (Karamihas et al., 2001).

The nominal curvature of a jointed PCC slab depends on factors such as base support, slab length, layer thickness and strength, reinforcement, joint type, and temperature and moisture of the concrete material during curing. All jointed concrete pavements are usually curled in one direction or another.

It was also observed that all the pavements with dense graded aggregate base decreased in roughness throughout the day, possibly because the base is not bonded like others, so there is less resistance to curling. In the case of a pavement with a bonded, lean concrete base, a very large change in roughness was observed, as shown in Table 4. This table shows the changes in MRI by structural design. The base types considered in the study were dense-graded aggregate base (DGBA), permeable asphalt-treated base (PATB), and lean concrete base (LCB). The increase in roughness observed in this experiment was of lesser magnitude than the decrease in roughness because much lower thermal stress is needed to lift the pavement edges than to push them down (Karamihas et al., 2001).

Effect of Built-in Curvature on Roughness

Slabs that curl upwards or downwards exhibit distinct profiles (Perera et al., 2001). Figure 15 shows a slab with joint spacing of 9 m, which is curled downwards, i.e. its joints are at lower elevation compared to center of the slab. Figure 16 shows a slab with joint spacing of 15 m, which is curled upwards. This curvature is a result of locked-in curvature in the slab that occurs during construction. The locked-in curvature is due to construction conditions or is related to moisture variation in the slab.

Factors Affecting Overall Smoothness in Concrete Pavements

A report prepared by Perera et al. (2001) for the National Cooperative Highway Research Program relates factors such as pavement structure, rehabilitation techniques, climatic conditions, traffic levels, layer materials and properties, and pavement distress to changes in pavement smoothness. The Level E data from the Long Term Pavement Performance (LTPP) Information Management Systems (IMS) were used by Perera et al. (2001) to evaluate the effects of the above-mentioned factors.

Jointed Plain Concrete (JPC) pavements exhibited higher values of International Roughness Index in areas where there was a higher precipitation amount, a higher freezing index, and a higher content of fines in the sub-grade. In the non-freeze regions, lower values of IRI were noted in pavements located in areas having daily temperature in excess of 32 °C and in pavements having lower elastic modulus values. Also, non-doweled pavements increased in roughness at a higher rate compared to doweled pavements. Pavements were classified as poor if the IRI satisfied the following condition: $IRI > 1.263+0.0947 \times Age$. Out of the pavements classified as poor, 71 percent were located in a wet freeze region, 24 percent in a dry freeze region, 6 percent in a wet no-freeze region, and 0 percent in a dry no-freeze region. Higher IRI values were related to higher freeze index values, higher freeze thaw cycles, and higher annual days below 0 °C. Pavements in warmer climates had lower IRI. Evaluation of the subgrade type indicated 67 percent of sections constructed on fine-grained subgrade had a poor IRI performance, whereas only 33 percent constructed on coarse grained soils showed poor IRI performance. Sections stabilized by asphalt had very low IRI. In the poor performance category, 82 percent of the sections had granular bases, whereas only 18 percent had stabilized bases.

Jointed Reinforced Concrete Pavements (JRCP) exhibited higher values of IRI in areas with higher precipitation, higher moisture content in subgrade, thicker slabs, longer joint spacing, lower water cement ratios, and higher modulus values for PCC. JRCP constructed on coarse-grained soils are found smoother compared to the ones on fine-grained soils, but no significant difference was found in case of pavements constructed on granular and stabilized bases. Thicker slabs exhibited higher IRI values compared to thinner slabs.

In cases of Continuously Reinforced Concrete Pavements (CRCP), lower IRI values were associated with higher longitudinal steel percentages and higher water cement ratios for PCC mix, whereas higher IRI values were associated with a higher PCC modulus. In non-freezing areas, higher values of IRI were noted in areas that had higher numbers of days above 32 °C. It was also found that 63 percent of pavements that rated poor were constructed over fine-grained subgrade, whereas 37 percent of the pavements that rated poor were constructed on coarse-grained subgrade.

The study of the data from Special Pavement Studies (SPS-2) sections provided the following observations:

- Average early age IRI for 200 mm thick PCC pavements was 1.27 m/km. For 275 mm thick PCC pavement, it was 1.30 m/km.
- A statistical test indicated no significant relationship between early age IRI and PCC thickness.
- Out of the three different base materials [Dense Graded Aggregate Base (DGAB), Lean Concrete Base (LCB), and Permeable Asphalt Treated Base (PATB)], highest early age IRI was obtained for PCC placed over LCB.

- It was noticed that the increase or decrease in roughness was primarily caused by change in slab curvature. The changes in slab curvature were not due to temperature variation and may have been caused by changes in moisture conditions in the PCC slab over time.

Perera et al. (2001) also examined the data from three General Pavement Studies (GPS) experiments: GPS-3 (jointed plain concrete pavements), GPS-4 (jointed reinforced concrete pavements), and GPS-5 (continuously reinforced concrete pavements). The test sections in each group were categorized according to the environmental conditions and subgrade type. Researchers then conducted an evaluation of change in roughness that occurred at each test section over the monitoring period.

For JPC pavements, it was observed that non-doweled sections showed more increase in roughness compared to doweled sections. In the non-doweled sections, a higher rate of increase was observed in pavements that reached a roughness level between 2.0 to 2.5 m/km. It was also observed that doweled sections showed less variation in IRI (caused by curling and warping) compared to non-doweled sections. Researchers reasoned that this is because the dowels provide some restraint against curling and warping that minimizes variation in profile. However, no distinct differences in trends in roughness development were noted for different types of bases. An analysis performed to investigate the factors that have an effect on roughness showed some noted trends, as given below. The trends are presented separately for doweled and non-doweled pavements.

Trends for Non-Doweled Pavements (see Table 5)

- <u>PCC Strength Parameters:</u> Higher IRI values were observed with increasing PCC modulus, PCC compressive strength, and Poisson's ratio. A strong relationship was observed between IRI and the ratio between PCC elastic modulus and PCC tensile strength. Several regions that had high values for this ratio had high rates of increase in roughness. With respect to the dry regions, no relationship was seen between PCC elastic modulus and IRI, but a strong relationship of the same was observed in the wet regions. Generally in the wet region, sections with PCC elastic modulus greater than 35,000 MPa had high IRI values.

- PCC Mix Parameters: No relationship between PCC mix parameters, such as coarse aggregate content, fine aggregate content, cement content, coarse-to-fine aggregate ratio, and water cement ratio were noted in the dry region. However, in the wet regions, higher IRI values were noted in sections with higher amounts of coarse aggregate and higher coarse-to-fine aggregate ratios. Also, a high rate of increase in IRI was noted in sections having water cement ratios of less than 0.35.

- Subgrade Properties: Subgrades with higher moisture content indicated higher IRI values. Subgrades with high clay contents and with higher plasticity indices showed higher IRI values (especially for wet regions). A higher rate of increase of IRI was noted in subgrades with a higher moisture content.

- Environmental Conditions: Higher IRI values were noted in pavements subjected to higher amounts of precipitation. The rate of increase in IRI was also higher in cases of pavements with higher numbers of wet days. Areas with low annual temperature showed higher IRI values. Pavements in areas that had a high number of days above 32 °C showed lower IRI values, as well as a lower rate of increase of IRI, compared to pavements in the areas with a low number of days above 32 °C. This may be because at higher temperatures, jointed slabs expand and provide better load transfer, which reduces the stress on the sub-surface layers and decreases the potential for faulting. Also, in the areas with high freezing indexes, the roughness of pavement increases due to frost heave effects.

- Trends for Doweled Pavements: The relationship observed between the parameters and IRI was weak in the case of doweled pavements on account of very low changes observed in roughness over the monitoring period.

- PCC Strength Parameters: No significant relationship was observed between the PCC elastic modulus and tensile strength with IRI. (Generally, non-doweled pavements having PCC elastic modulus greater than 35,000 MPa showed high IRI values. However, only four doweled sections with PCC elastic modulus greater than 35,000 Mpa were available for analysis. Data insufficiency may have an effect on this hypothesis).

- Environmental Conditions: A weak trend of higher IRI with high wet days was noted. Sections in areas with high freezing indices showed high rates of increase in IRI.

With respect to jointed reinforced concrete pavements, the different factors considered to determine the effect on the median IRI or the rate of change of IRI are as follows (see Table 6):

- PCC Strength Parameters: The observed trends were generally weak. Lower IRIs were noted for higher compressive strength of PCC and higher unit weight of PCC. Higher IRI values were noted for higher PCC elastic modulus, higher PCC Poisson's ratios, and higher ratios between PCC elastic modulus and PCC tensile strength.

- PCC Mix Parameters: In general, higher IRI values were noted for sections that had low cement content (<300 kg/m3) and in sections that had water cement ratios in excess of 0.5.

- Subgrade Properties: Higher IRI values and higher rates of increase of IRI values were noted for sections with higher moisture contents, higher clay contents, and higher plastic limits.

- Environmental Conditions: Higher IRI values were noted in pavements subjected to higher amounts of precipitation and having higher mean temperatures (higher temperatures cause spalling due to expansion of the pavement, which is responsible for the roughness). The rate of increase in IRI was also higher in cases of pavements with higher numbers of wet days.

- Pavement Design Parameters: Higher values of IRI were noted for thicker PCC slabs. Also higher IRI, as well as higher rates of increase of IRI, was noted in cases of pavements with higher joint spacing. (Increased spacing generally results in increased transverse cracking and, hence, increases spalling and faulting potential of the pavement).

With respect to continuously reinforced concrete pavements, the analysis indicated that factors such as high PCC modulus, high PCC modulus and PCC tensile strength ratios, high Poisson's ratios, low water cement ratios, and low total pavement thickness (where total thickness is the sum of surface, base and sub-base layers) contribute to higher IRI values. The noted trends from an analysis performed to investigate the factors having an effect on the roughness of GPS-5 pavements are as follows (see Table 7):

- PCC Section Parameters: A weak trend of lower IRIs was noted for higher total PCC thickness. No relationship was noted between the IRI values and the base type. In the wet no-freeze zone, lower IRI values were associated with higher steel contents.

- Subgrade Properties: In the wet freeze zone, higher IRI values were noted for sections with higher moisture contents and higher percentages passing the No.

200 sieve. For both wet freeze zones and wet no-freeze zones, higher IRIs with higher plasticity index were noted.

- Environmental Conditions: Higher IRI values were noted in pavements with higher wet days per year in cases of wet freeze zones, whereas lower IRI values with higher numbers of wet days were noted for wet no-freeze zones. Higher wet days result in an increase of frost heave potential of the subgrade in the freezing regions due to an increase in moisture content. This results in additional roughness. In the wet no-freeze zones, precipitation maintains constant moisture content in the subgrade and reduces the shrinking and swelling of the subgrade.

- Pavement Strength Parameters: An increase in IRI values was observed with increasing PCC modulus. A strong relationship was observed between IRI and the ratio between PCC elastic modulus and PCC tensile strength. (A high value of elastic modulus compared to its split tensile strength may exhibit more brittle behavior, resulting in higher IRI values).

- PCC Mix Parameters: Lower values of IRI were observed for sections with higher water cement ratios.

Effect Of Initial Pavement Smoothness On Pavement Performance

A study conducted by Smith et al. (1997) provides some insight on the effect of initial smoothness on pavement performance. It documents effects of initial smoothness on future pavement smoothness and pavement life.

Design equations developed from the AASHO Road Test (1962) imply that initial smoother pavements maintain higher levels of ride quality. A study that analyzed historical roughness data spanning 10 years and representing about 400 sections in Arizona and Pennsylvania related initial smoothness to long term roughness, as illustrated in Figure 17. Also, examination of the state highway agency (SHA) data indicated that pavement sections built smoother generally remain smoother over time. In the case of pavements of similar design but of different initial smoothness, it is seen that the less smooth sections deteriorate faster (dynamic loading/greater variability in construction). Table 8 summarizes the percentage of projects for which initial smoothness had a significant effect on the future smoothness of the pavement. Though there is some variability from state to state and pavement type to pavement type, the overall trend indicates that initial smoothness has a significant effect on the future smoothness of pavements.

In evaluating the relationship between initial smoothness and pavement life, two different approaches were undertaken. The primary strategy involved the development of models for each project using regression analysis of the available time series roughness data. Each project model was used to predict, for various initial smoothness levels, the service lives associated with the pavement reaching a terminal roughness level. The second approach consisted of analyzing time series roughness data and the corresponding actual pavement failure data for limited pavement projects. Both approaches yielded results indicating that initial pavement smoothness has a significant effect on pavement life. The rate at which additional life is achieved is dependent upon, among other things, pavement type, facility type, and location. An analysis was carried out to determine the percent change in life as a function of the percent change in initial smoothness. At the very least, a 9 percent increase in life corresponding to a 25 percent increase in initial smoothness was observed. Target profile indices of 7 inch/mi (0.2 inch blanking band) for concrete pavement were considered in this study. A 50 percent increase in smoothness from these target levels was found to increase life, at the very least, by 15 percent in most of the cases.

Factors Affecting the Quality of Profile Data Collection

There are several factors related to the profilometer, the environment, the operation of the profiler, and others that affect the quality of the data collected. Malfunctioning of profiler equipment, such as height sensor, distance measuring equipment, or accelerometer affect the profile data. Environmental factors that affect the profile are surface contaminants and surface moisture present on the pavement at the time of data collection. Among factors related to operation of profiler are operating speed of the profiler, speed changes during profiling, lead-in distance required prior to the section, lateral positioning within a section, and correct data information at the start of the section. The Federal Highway Administration report on Long Term Pavement Performance (LTPP) data variability (Evans et al., 2000) identified unnoted equipment related saturation spikes, partial and complete lost lock, and mis-calibrated distance measuring instrument (DMI) as among the major factors that cause data variability.

- Effect of Saturation Spikes: Saturation spikes are caused due to excessive reflection of light into the optical sensor receivers of a profilometer. The effect of unedited saturation spikes on IRI, using spikes of various amplitudes, was analyzed. The relationship between spike amplitude and IRI is nearly linear, with a 1.8 percent increase in average IRI for every 5 mm increase in spike amplitude. This evaluation showed that spikes in the range of 12 to 75 mm have a significant effect on the IRI and, hence, saturation spikes greater than 5 mm should not be included in profile smoothness statistical computation.

- Effect of Lost Lock in Profiles: Lost lock is caused when the optical sensors do not receive enough reflected light to determine a pavement elevation. In case of concrete pavements, lost lock may generally occur when the sunlight or beam passes beneath the covering shrouds, making the ambient light condition too bright for the sensor to determine the elevation correctly. Due to lost lock, a fine saw-tooth type profile is obtained. Generally, higher IRI values are obtained due to rapid changes in profile elevation caused by lost lock.

- Effects of DMI Mis-calibration: The DMIs for profilometers are usually mounted on the front wheel. Evans and Eltahan (2000) noted that mis-calibration of DMI affects profiles by including too little or too much profile data in a section. The researchers found that mis-calibration of DMI was significant in the North Central Region, where 3.1 percent of the profile runs were off by 6 to 8 m. Observations from evaluation of the LTPP profile data show that DMI mis-calibration results in squeezing of the profile so that data points are collected at slightly more than 152.4 m, the length of an LTPP test section. As a result, the data files contain slightly more profile than the actual section length and results in IRI values that are greater than the true values.

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Figure 1. Placer Spreader.

The above photo shows a placer spreader that leads the paving train and spreads the concrete along the width of the pavement. It is equipped with hydraulic, pressure-compensated adjustable side-plates. The belt conveyor system transfers the concrete from the tipper onto the road surface in front of the spreader.

Figure 2. Close-up View of Spreader Showing Auger.

The above picture shows a close view of the spreading auger. Cradles holding dowel bars can be seen in the picture.

Figure 3. Picture of a Paver.

The above photo shows a paver that follows the spreader in the paving train. Vibrators can be seen immersed in the concrete. A fork on the left of the photo follows the string line.

Figure 4. Finishing Tube with Motorized Carrier.

In the above photograph, a tube is used to level the concrete surface ahead of the finishers. The tube is mounted diagonally along the width of the pavement. This pushes material to the sides as the tube is dragged back and forth along the concrete surface. There is no force applied to the tube as chains to the motorized carrier only support it. The concrete surface is leveled by the weight of the tube as it is dragged along the pavement.

Figure 5. Straightedge Used for Hand Finishing.

Manual finishing is carried out by using a straightedge (10-, 12-, 16-, and even 20-ft straightedges are used).

Figure 6. Illustration of Paving Train.

The above photograph shows a paving train with spreader, followed by a paver and a finisher.

Figure 7. Auto Float Marketed by Gomaco.

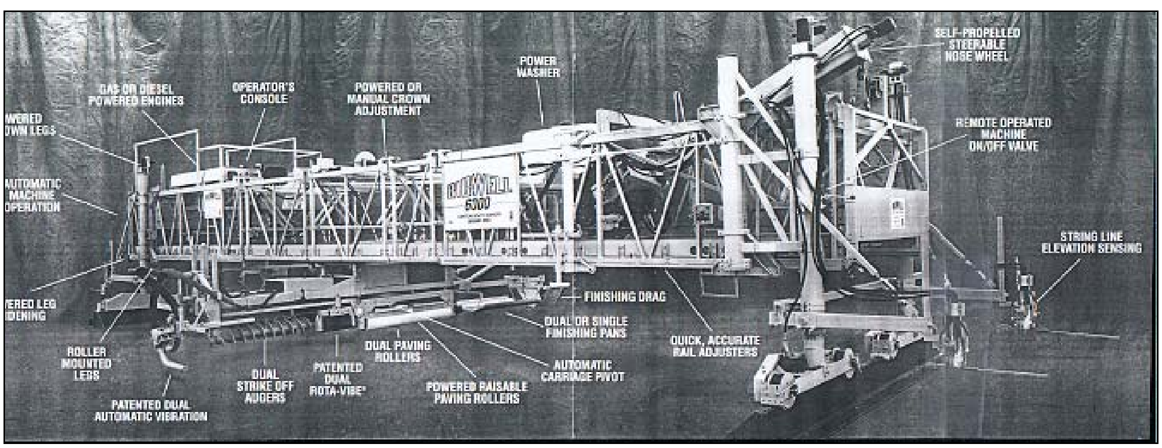

Figure 8. Deck Paving Machine.

Figure 9. Mechanical Finisher for Bridge Decks.

Figure 10. Bidwell Paving Machine Used in San Antonio Project.

The above photo shows mechanical finishing in progress. A cylindrical finisher is used in paving operations to give a smooth finish to the pavement.

Figure 11. Texture and Curing Equipment.

The above photo shows texture and curing equipment. It travels transversely across the width of the concrete slab. Texturing wire tine member is automatically pivoted to trail at the end of each pass. Contact pressure between texturing member and concrete may be varied to control the depth and angle of wire tines. The curing compound is then sprayed on the slab.

Figure 12. Real Time Profiler Developed by Ames Engineering.

Figure 13. Fifth Wheel Used to Measure Distance in Real Time Profiler.

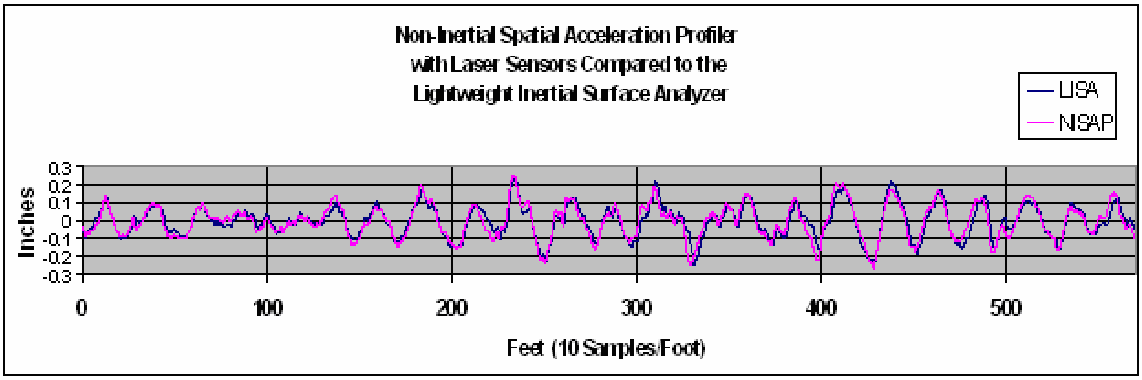

Figure 14. Comparison of Data from Real Time Profiler and from Lightweight Inertial Profiler.

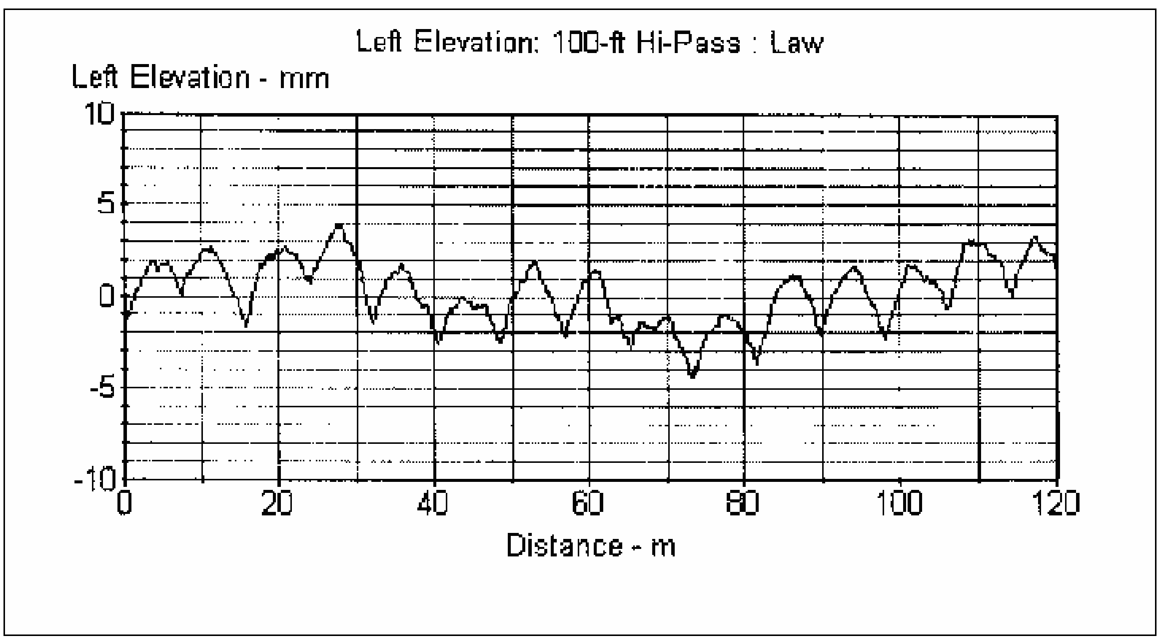

Figure 15. Profile Showing Slab with Joints Curled Downwards (Perera et al., 2001).

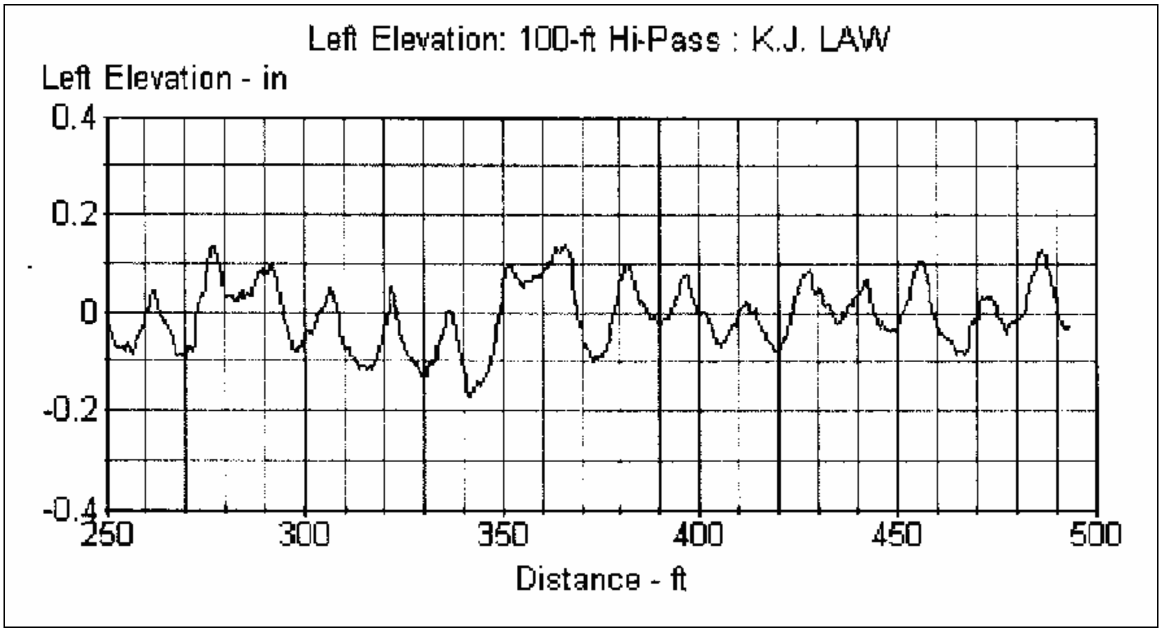

Figure 16. Profile Showing Slab with Joints Curled Upwards (Perera et al., 2001).

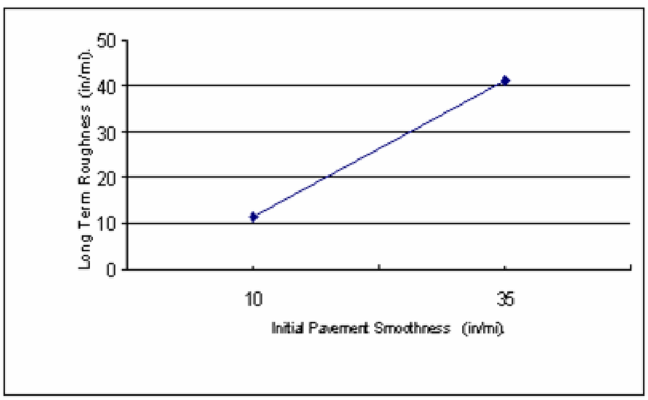

Figure 17. Initial Pavement Smoothness vs. Long-Term Pavement Roughness as Measured with the Mays Meter (Janoff, 1991).

Table 1. List of Equipment Manufacturers Surveyed.

Equipment Manufacturer	Phone Number
Ingresoll Rand Worldwide *Contact person:* Mr. Steve Weal	(217) 238 - 6217 or (217) 234 - 8811
Closner Equipment *Contact person:* Mr. Frank Closner	(210) 732 - 2131
C.M.I. Corporation *Contact person:* Mr. Chapin Sipherd	(405) 787 - 6020
Carlson Paving Products *Contact person:* Mr. Ray Ericsson	(253) 875 - 8000
Midland Machinery Co., Ltd.	(796) 692 - 1200
Gomaco Corporation *Contact persons:* Mr. Denis Clousen, Mr. G. Doberson	(712) 364 - 3347
Way Equipment Corporation	(315) 474 - 1567
Cedarapids Paving Group	(319) 363 - 3511

Table 2. Change in Slab Curling with Aging of Concrete Slab (Rao et al., 2001).

Concrete Age	Measured Curl	Equivalent Temperature Gradient (°C/cm)	Equivalent Temperature Differential (°C)
Set time	+7.3	-0.4	-7.3
3 days	-4.2	-1.0	-22.2
15 days	-2.0	-0.7	-14.7
40 days	-3.2	-1.3	-27.4
2 years	-3.9	-1.0	-21.9

Table 3. Effect of Thermal Changes on IRI Measurements (Karamihas et al., 2001).

Section	MRI from earliest measurement (m/km)	MRI change (m/km)
260217	0.92	no change
260213	1.45	-0.40
260221	0.99	+0.10
260224	1.01	no change
260216	1.39	-0.30
260220	1.34	-0.40
260215	1.26	-0.15
260223	0.19	no change
260222	1.16	-0.20
260253	1.14	+0.20
260214	2.08	-0.40

Table 4. Effects of Pavement Design Variables on Concrete Smoothness (Karamihas et al., 2001).

Layer 1 Thickness (cm)	PCC Flexural Strength (MPa)	Change in MRI (m/km)		
		DGBA	PATB	LCB
20.30	3.66	-0.40	+0.10	no change
20.30	4.27	-0.40	-0.20	–
27.90	3.66	-0.15	+0.05	–
27.90	4.27	-0.30	no change	-0.40

Table 5. Factors Affecting Roughness Progression in Non-Doweled PCC Pavements.

No.	Parameter	Effect of higher value of parameter on roughness	Comment
1	PCC elastic modulus	Increases	Note 1
2	PCC compressive strength	Increases	Note 2
3	PCC Poisson's ratio	Increases	
4	Ratio between PCC elastic modulus and PCC tensile strength	Increases	Note 3
5	Subgrade clay content	Increases	Stronger relationship in wet zone
6	Subgrade plasticity index	Increases	
7	Subgrade moisture content	Increases	
8	Annual precipitation	Increases	
9	Mean temperature	Increases	
10	Faulting	Decreases	

Note 1: Seen for PCC modulus > 35,000 MPa.

Note 2: Seen for PCC compressive strength > 60 MPa.

Note 3: Seen for ratio > 8000.

Table 6. Factors Affecting Roughness Progression in JRCP Pavements.

No.	Parameter	Effect of higher value of parameter on roughness
1	PCC elastic modulus	Increases
2	PCC compressive strength	Decreases
3	PCC unit weight	Decreases
4	PCC Poisson's ratio	Increases
5	Ratio between PCC elastic modulus and PCC tensile strength	Increases
6	Sub grade clay content	Increases
7	Sub grade plasticity index	Increases
8	Sub grade moisture content	Increases
9	Annual precipitation	Increases
10	Wet days	Increases
11	Mean temperature	Increases
12	Joint spacing	Increases

Table 7. Factors Affecting Roughness Progression in CRCP Pavements.

No.	Parameter	Effect of higher value of parameter on roughness	Environmental Zone
1	PCC elastic modulus	Increases	For both wet freeze and wet no-freeze zone
2	Ratio between PCC elastic modulus and PCC tensile strength	Increases	
3	PCC water cement ratio	Decreases	
4	Sub grade fine content	Increases	Wet freeze zone
5	Wet days per year	Increases	
6	Sub grade moisture content	Increases	
7	Steel content	Decreases	Wet no-freeze zone
8	Wet days	Decreases	
9	Days per year > $32^{o}C$	Increases	
10	Mean annual temperature	Increases	

Table 8. Summary of Significance of Initial Smoothness (Smith et al., 1997).

State	Number of significant projects / Total Number of projects for PCC Pavements	
	Total Number	Percentage
AL	26/26	100
AZ	11/17	65
GA	4/6	67
IL	15/20	75
KY	6/6	100
MI	6/6	100
MN	1/3	33
SD	11/13	85
WA	5/6	83
WI	28/39	72
TOTAL	113/142	80

APPENDIX B
The Ames Real Time Profiler

During the course of this project, researchers found (from information provided by the project director) that Ames Engineering was developing an instrument to measure profiles on concrete surfaces while the concrete was being placed. Since this development work was on-going at the time Project 0-4385 began, researchers met with Ames Engineering staff to get available information on the company's Real Time Profiler and assess the potential for its implementation in Texas. Figure 1 shows a picture of the Ames RTP mounted on a test cart the company uses for taking measurements on existing pavements. The sensors used for profile measurements consist of three lasers housed inside the bar attached to the bottom of the cart shown in Figure 1. At the time researchers met with Ames Engineering staff in May 2002, the company had already tested the RTP on actual concrete paving projects. Ames also had compared the RTP with its Lightweight Inertial Surface Analyzer (LISA) based on measurements made on an existing concrete pavement. Figures 2 and 3 show the available information from these initial tests. As may be observed, the agreement with the LISA (Figure 2) and the repeatability of the RTP measurements (Figure 3) are quite good. At the time researchers met with Ames Engineering, a couple of LISA units had already undergone certification at TTI based on TxDOT Test Method Tex-1001S. Thus, the company used the LISA to conduct its evaluation of the RTP. Researchers note that these tests were conducted using a cutoff wavelength of 50 ft, the upper limit of the wavelengths that can be measured, from communications with Ames Engineering.

To assess the potential of the RTP as a tool for quality control/quality assurance (QC/QA) of pavement smoothness during placement of Portland cement concrete mixtures, researchers conducted an evaluation that consisted of:

- collecting profile data on simulated bumps with known profiles,
- determining the repeatability of the RTP profiles and accuracy of International Roughness Indices (IRIs) computed from RTP data, and
- comparing the performance of the RTP with the Ames Model 6000 lightweight profiler.

The following sections present the tests conducted and the findings from this evaluation.

Figure 1. Picture of Ames Real Time Profiler (red painted lines on pavement indicate locations of three lasers).

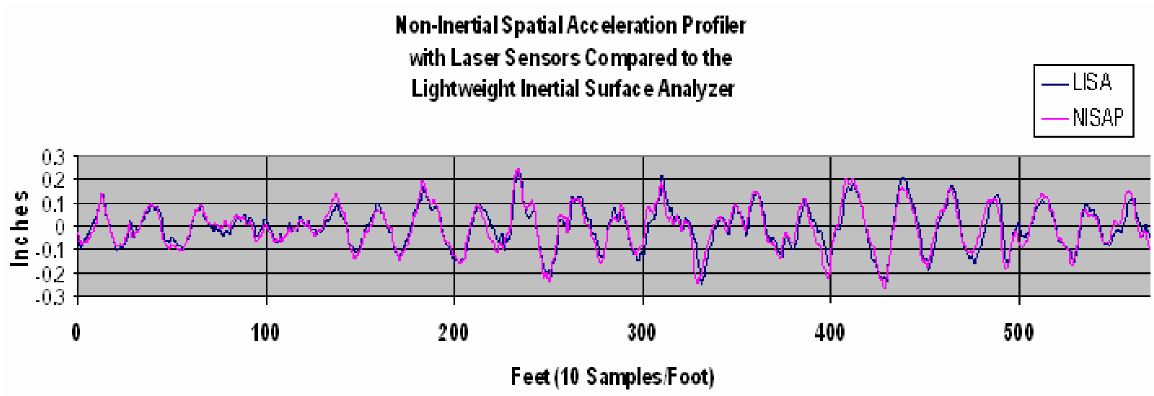

Figure 2. Comparison of Profiles Measured with the RTP and LISA (from tests conducted by Ames Engineering).

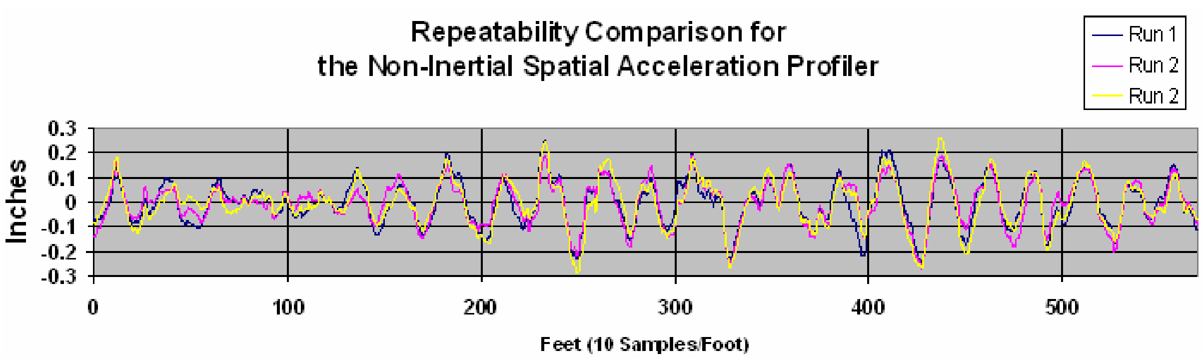

Figure 3. Repeatability of RTP Measurements (from tests conducted by Ames Engineering).

Test Program

The test program to evaluate the RTP included the following tasks:

- collection of reference profiles on wheel paths of test section,
- measurement of simulated bump profiles, and
- collection of profile data with the Ames RTP and Model 6000 lightweight profiler.

The test section selected for this evaluation is a 528-ft overlaid flexible pavement located at the south end of runway 35L at the Texas A&M Riverside Campus. To provide a reference for evaluating the accuracy of IRIs computed from the test profiles, researchers measured the wheel path profiles using the Walking Profiler and rod and level, following the procedure given in TxDOT Test Method Tex-1001S. Researchers note that the IRI is used for acceptance testing of pavement surfaces in the current TxDOT smoothness specification (Item 585). Thus, the repeatability and accuracy of the IRIs computed from the test profiles were determined.

Of particular interest in this project is the potential application of the RTP as a tool for detecting localized defects during placement of Portland cement concrete mixtures. Thus, the test program included measurements on simulated bumps. Figure 4 illustrates one of two bumps used during testing. To measure the bump profile, each bump was placed on a level granite table certified to be within 0.0005 flatness. Technicians then took elevation readings at 0.25-inch intervals along the bump centerline using the Heightmatic gauge shown in Figure 4 that gives readings to the tenth of a mil. From this profile, researchers determined the height of each bump.

Figure 4. Measuring the Bump Profile in the Laboratory.

Table 1 shows the tests made with the bumps. Researchers conducted three series of tests designated as series 0, 1, and 2 in the table. These test series are described as follows:

- In series 0, the RTP and the Ames Model 6000 profiler were each run ten times on the test wheel path with no bumps placed on the wheel path.
- In series 1, profile data were collected with a single bump placed on the test wheel path according to the sequence, 1a – 1b, given in Table 1. For each sequence, five runs were made with the RTP and another five with the Ames Model 6000 profiler.
- In series 2, two bumps were placed on the test wheel path. Five runs were then made with each profiler according to the sequence, 2a – 2b, given in Table 1. Figure 5 illustrates a test run made under series 2a.

Table 1. Field Tests Made on Simulated Bumps.

Test series	Bump ID	Bump placement[1] (ft)	Bump height (mils)
0	No bumps	N/A	N/A
1a	2	250	538
1b	5	383	1116
2a	2	250	538
	5	259.5	1116
2b	2	250	538
	5	288	1116

[1] Distance of leading edge of bump from start of test section at 130 ft.

For all test series, Mark Leichty of Ames Engineering operated the RTP and the lightweight profiler and provided electronic files of the wheel path elevations according to the file format prescribed in TxDOT Test Method Tex-1001S. Results from these tests are presented in the following section.

Evaluation of Test Profiles Collected on Simulated Bumps

Researchers evaluated the profiles from the RTP to verify the performance of the instrument on known bumps and to determine its potential as a quality assurance (QA) tool for measuring the initial smoothness of Portland cement concrete pavements. For this purpose, researchers examined the profiles to determine the bump locations and bump heights for comparison with the known values. Figures 6 and 7 illustrate the profiles measured from repeat runs of the RTP on test series 1b and 2b. It is observed that the bumps stand out as peaks in the profiles and that the locations of these peaks are very consistent from run to run. Table 2 compares the locations of the bump peaks determined from the RTP with the reference locations determined by tape. The differences vary from 1.0 to 1.7 ft. Note that these errors are within the 8-ft length of each simulated bump. In the opinion of the researchers, the differences are acceptable and suggest that one can use the RTP profiles to locate where the simulated bumps were placed on the test section.

To determine the bump heights, one cannot simply take the magnitudes of the bump peaks shown in Figures 6 and 7 since the RTP gives filtered profiles. In an earlier project conducted for TxDOT, Fernando (1997) showed that the profile within the vicinity of a bump is distorted due to filtering of the data. This distortion is illustrated in Figure 8, which compares the RTP profiles taken with and without the bumps from test series 1b and 0, respectively.

Figure 5. Collection of RTP Data under Test Series 2a.

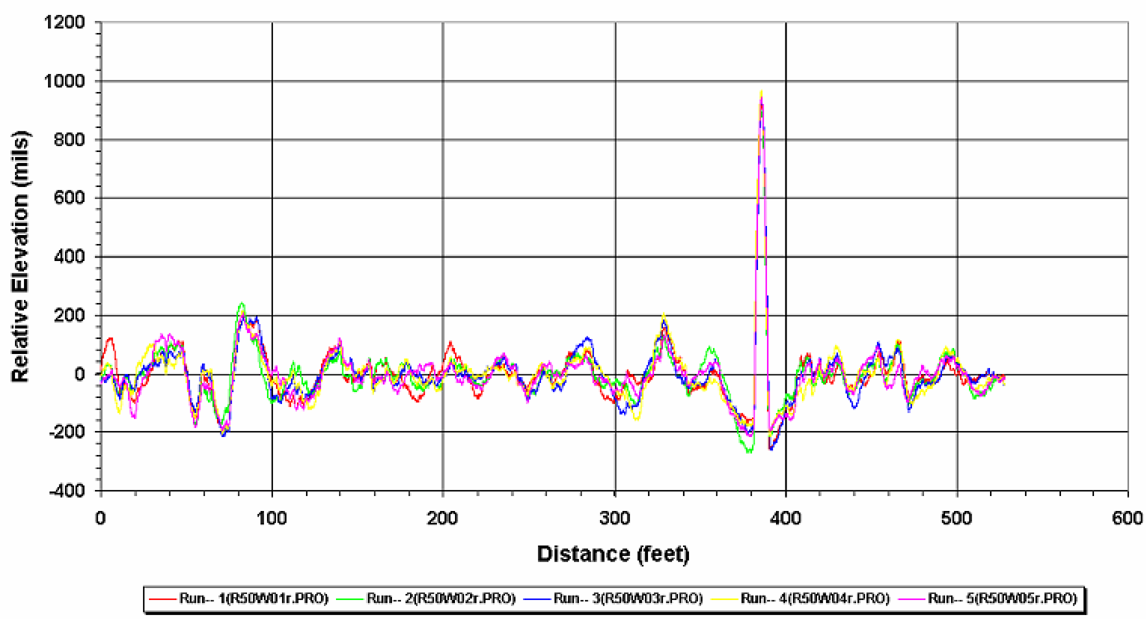

Figure 6. RTP Profiles Collected Under Test Series 1b.

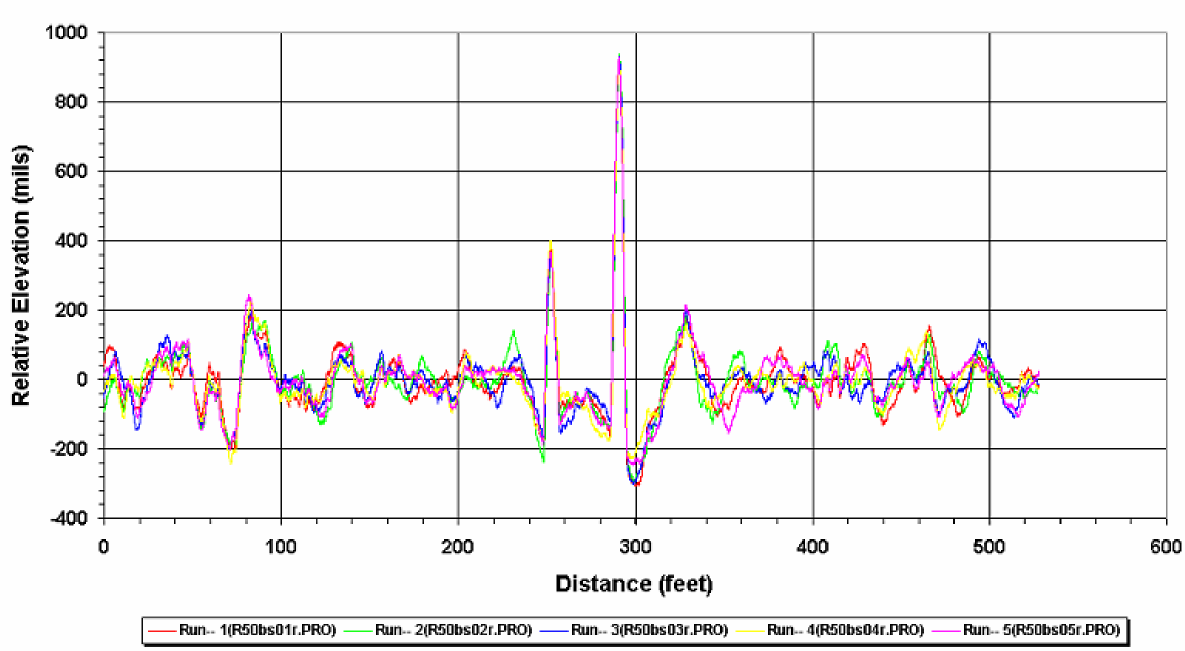

Figure 7. RTP Profiles Collected Under Test Series 2b.

Table 2. Locations of Bump Peaks Determined from RTP Profiles.

Test series	Bump ID	Bump location (ft)	
		RTP	Reference
1a	2	252.6	254
1b	5	386	387
2a	2	252.4	254
	5	262.4	263.5
2b	2	252.3	254
	5	290.8	292

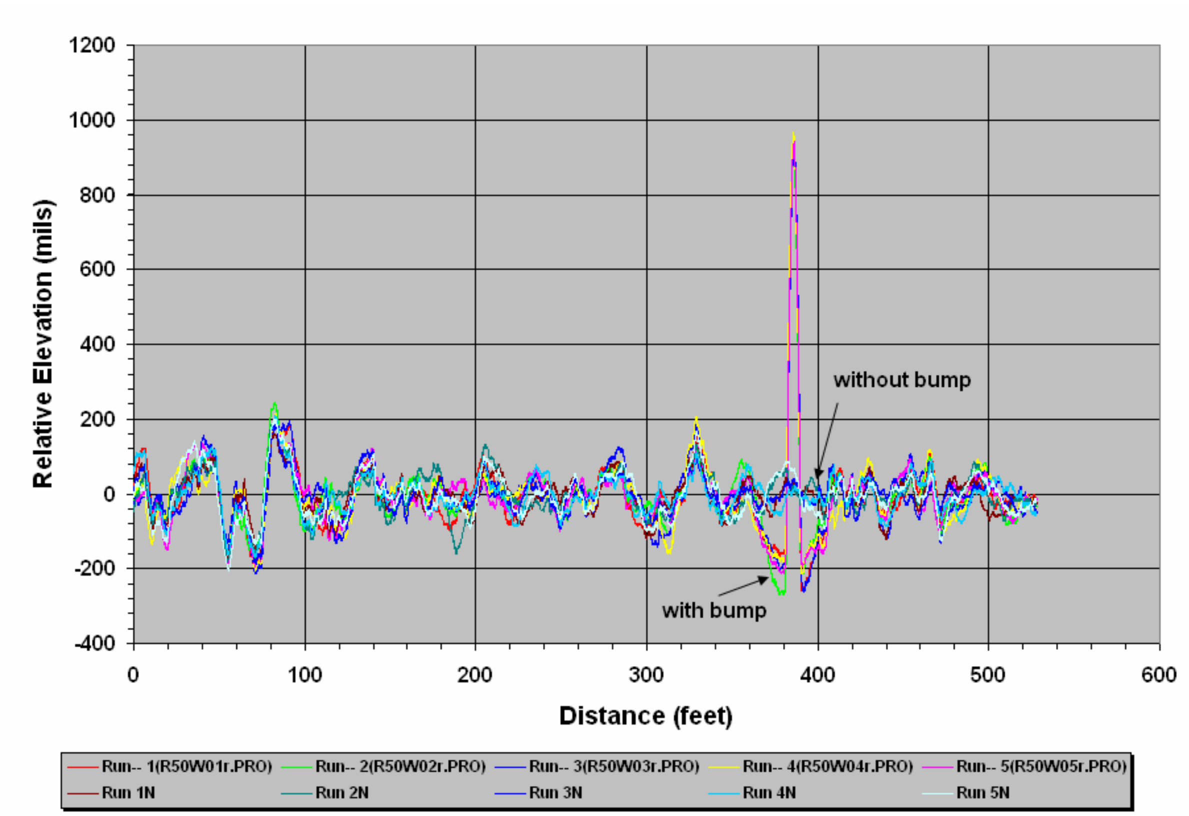

Figure 8. RTP Profiles Taken with and without Bump 5 (Test Series 1b and 0).

Note the artificial drops or dips in the profiles before and after the bump that are not observed in the RTP measurements taken without the bump on the test wheel path or from the reference data (Figure 9). With the reference or unfiltered data shown in Figure 9, one can determine the bump height by taking the difference in elevations (with and without the bump) at the location of the peak. However, since the RTP data is filtered, this same procedure cannot be applied with the profiles shown in Figure 8.

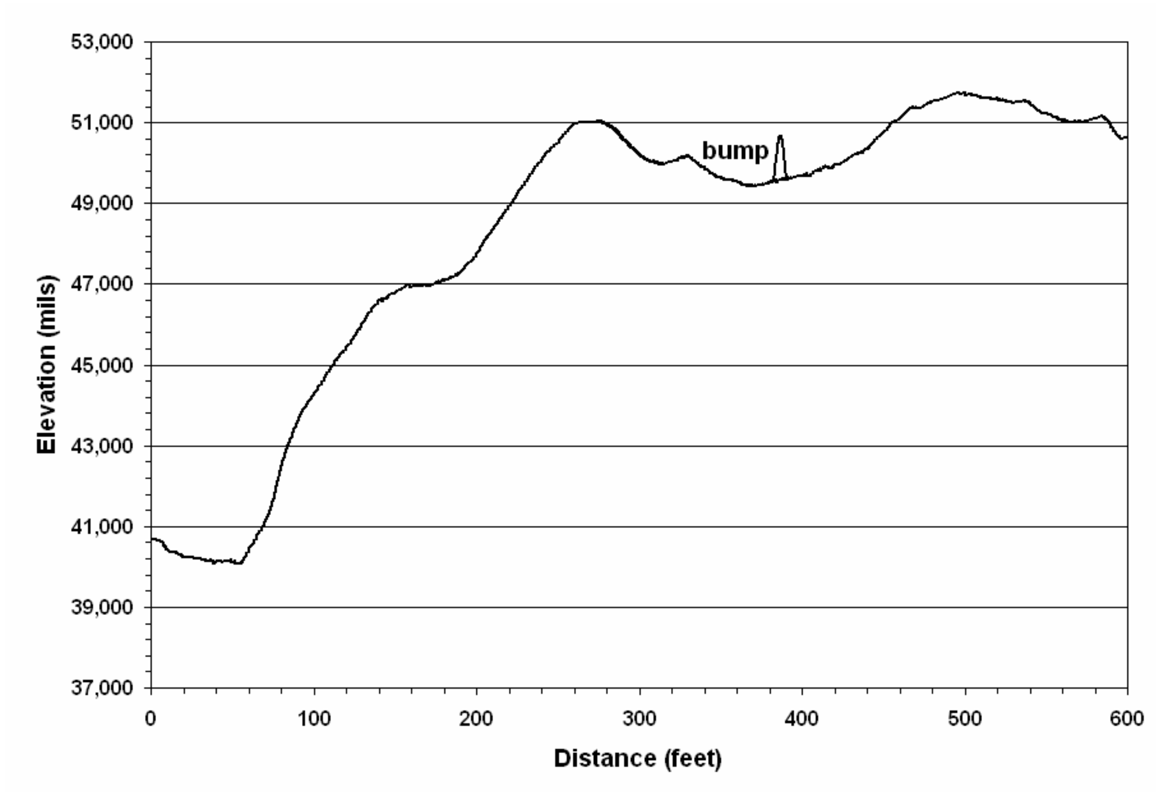

Figure 9. Unfiltered Wheel Path Profile with Bump 5.

To estimate the bump heights from the RTP profiles, researchers computed the differences in elevations at the peak locations and at two base points corresponding to the locations of the troughs immediately preceding and immediately following the peak. Thus, from a given profile, two bump heights (h_1 and h_2) were determined, as illustrated in Figure 10. Table 3 compares the bump heights determined using this approach with the corresponding reference values. The estimates given in the table are averages of the heights determined from repeat runs made with the RTP. The following observations are noted from Table 3:

- The h_1 estimates are generally closer to the reference values than the h_2 estimates. For the first case, the absolute differences range from 0 to 47 mils or from 0.0 to 8.7 percent of the reference values. For the second case, the absolute differences range from 0 to 87 mils or from 0.0 to 11.0 percent of the reference heights.

- The h_1 estimates exhibit less variability than the h_2 estimates. The standard deviations of the h_1 estimates range from 1.3 to 3.1 percent of the corresponding mean values compared to a range of 2.4 to 5.4 percent for h_2.

The above results suggest using h_1 with the RTP profile measured during concrete placement to estimate bump height. Researchers note that these results are based on the specific filter used with the RTP (third-order Butterworth with a cutoff wavelength of 50 ft).

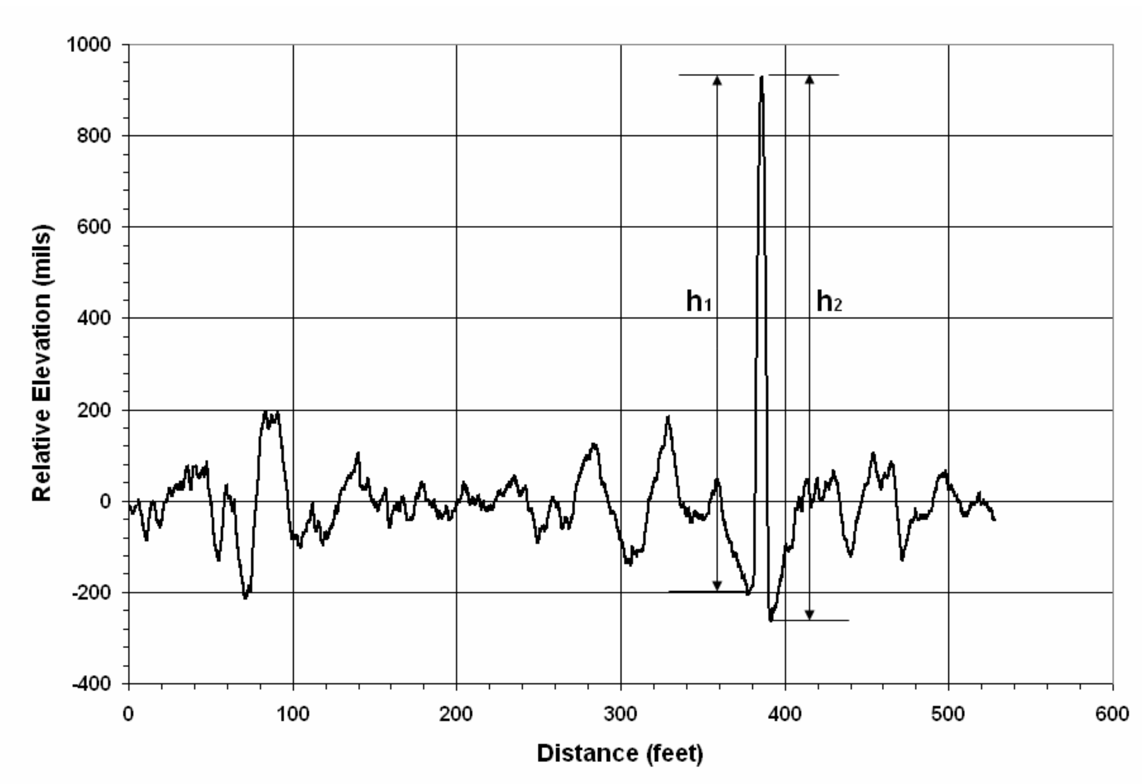

Figure 10. Bump Height Estimates Obtained from RTP Profiles.

Table 3. Bump Height Statistics from RTP Profiles.

Test series	Bump ID	Bump height statistic (mils)				Reference bump height (mils)
		Average		Standard deviation		
		h_1	h_2	h_1	h_2	
1a	2	546	492	9	27	538
1b	5	1145	1162	17	36	1116
2a	2	491	545	11	23	538
	5	1116	1116	14	26	1116
2b	2	562	479	17	24	538
	5	1073	1203	16	38	1116

Potential Application of the RTP as a QC/QA Tool

In terms of quality control, the results from tests on known bumps indicate that the RTP can potentially help a contractor build smoother concrete pavements by enabling him to detect defects as the concrete is placed and use finishers to correct these defects while the concrete is still plastic. This capability can thus minimize, if not eliminate, the amount of grinding that needs to be done to correct bumps after the concrete has set. This corrective action is costly to the contractor and leaves a permanent scar on the new pavement surface. This application would require that the RTP be set up to give bump locations and bump heights in real time and to alert and give this information to the contractor as the concrete is placed. The authors note that Ames Engineering might have already set up the RTP with this option, but this particular feature was not verified in the tests reported herein. In particular, if the RTP incorporates a method to estimate bump height from filtered data, this method may require additional tests for verification purposes.

In terms of quality assurance, the RTP does permit measurements to be taken on the finished surface (after tining). However, in the researchers' opinion, application of the RTP for acceptance testing of final surface smoothness runs into a number of issues, among which are:

- effect of tining on the laser measurements,
- effect of filter settings on the ride statistic computed from the RTP profile, and
- cost of providing an instrument for both QC and QA applications.

The first issue is particularly relevant for longitudinally tined concrete pavements. Addressing this issue may require the use of wide-spot lasers or bridging filters with the RTP, particularly in states where concrete pavements are longitudinally tined. However, since concrete pavements are transversely tined in Texas, the effect of tining (on repeatability of the ride statistic computed from profile) would not be significant, in the researchers' opinion.

The second issue, effect of filter settings, could affect the potential application of the RTP for acceptance testing on Texas concrete paving projects. The existing TxDOT ride specification requires a 200-ft cutoff wavelength for surface profile measurement compared with the 50-ft cutoff used with the RTP. Since the IRI is used for acceptance testing of pavement smoothness in Texas, the question arises as to the effect of this difference in cutoff on the ride statistic computed from profile. To assess the likely effect, one can look at the IRI gain function to identify the wavelengths or frequencies in the profile data that significantly influence this ride statistic. Figure 11 shows the IRI gain function from Sayers and Karamihas (1997). As observed from this figure, the gain is greater than 1 for wavelengths in the range of about 5.5 to 73 ft. To the extent that profile components above 50 ft that significantly influence this ride statistic are present, the difference in computed IRIs between 50- and 200-ft cutoffs could be significant. To verify this effect, researchers used the RTP data from test series 0 to compare the computed IRIs with corresponding statistics from the reference (unfiltered) profiles. From this analysis, the average and standard deviations of the IRIs from the RTP profiles were determined to be 78.9 and 3.3 inch/mile, respectively. The average IRI based on the reference (unfiltered) profiles is 97.1 inch/mile. Note that the IRI from the RTP underestimates the reference IRI by about 18 inch/mile. In contrast, the average IRI computed from the LISA profiles is 97.3 inch/mile, which is very close to the reference value. These results suggest that a 50-ft cutoff may not be wide enough to permit application of the RTP for acceptance testing of concrete pavement smoothness under the TxDOT ride specification, which is based on IRI. However, this particular application may be feasible under a smoothness specification that is based on a different profile statistic, particularly one that is not significantly affected by wavelengths greater than 50 ft.

Finally, the cost of QC/QA equipment for evaluating concrete surface smoothness during construction needs to be considered. While it may be possible to develop an instrument that can be used for both QC and QA purposes, cost will be a deciding factor in whether it gets used. In practice, multiple units would have to be deployed to measure multiple wheel paths at the same time. For the purpose of detecting defects as the concrete is placed, units would have to be mounted behind the paver to check the different wheel paths. Likewise, additional units would have to be located behind the tining machine if the same method is to be used for quality assurance testing. The amount of development work and the sensors required to make an instrument for the latter application will entail more cost, particularly if it becomes necessary to estimate longer wavelengths.

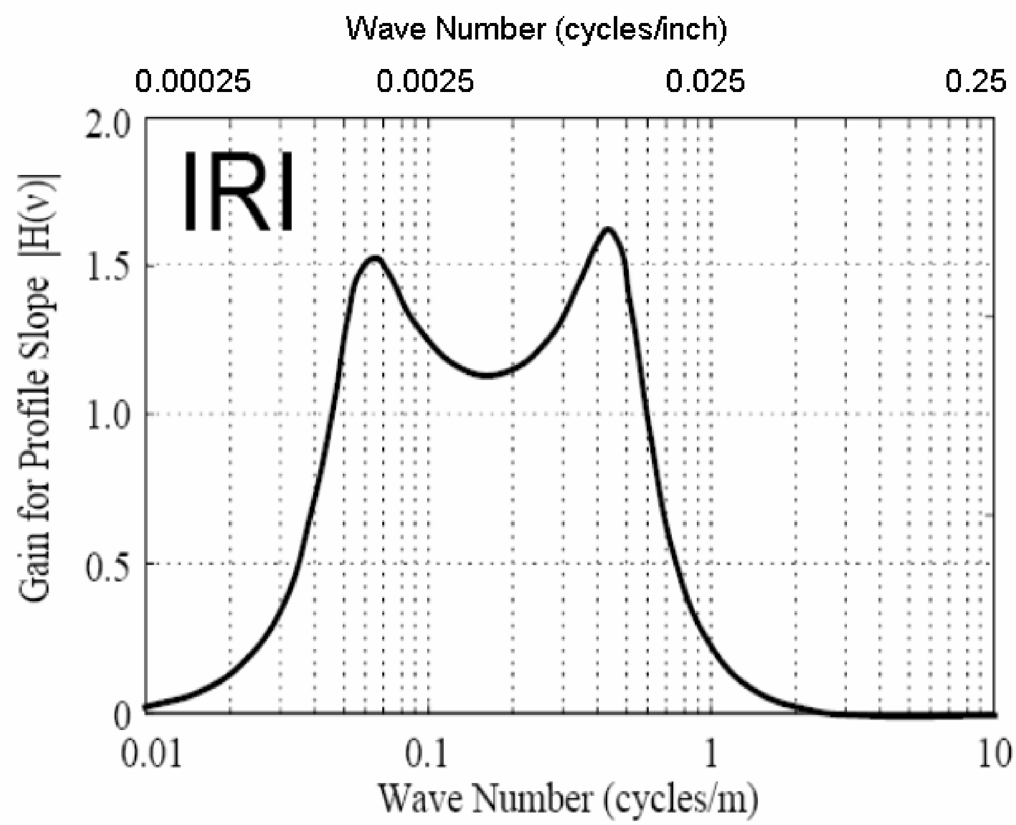

Figure 11. IRI Gain Function (Sayers and Karamihas, 1997).

In view of these considerations and based on the results from the tests conducted, the authors offer the following opinions:

- The most feasible application of the RTP tested during this project is for detecting defects during concrete placement to minimize, if not eliminate, the need for grinding to remove bumps after the concrete has set.
- The 50-ft cutoff wavelength used with the RTP precludes its application for quality assurance testing of the finished concrete pavement surface under the existing TxDOT ride specification. Perhaps the RTP can be modified to permit measurement of longer wavelengths, but this effort could entail more development work and add to the cost of the equipment. Rather than moving in this direction, quality assurance testing of concrete pavements can simply be conducted using inertial profilers, as provided for in the existing ride specification.

If the concern is to have an instrument that can be used for bump detection during concrete placement, cheaper sensors are available that can be used to develop a tool for this purpose. The paving industry would certainly be more receptive to using a piece of equipment that improves their product, provides reliable measurements, and is easy to use and own.

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Sayers, M. W. and S. M. Karamihas. *The Little Book of Profiling.* Transportation Research Institute, University of Michigan, Ann Arbor, Michigan, 1997.